
‘Fliegen Sie das Teleskop’
NASA
DLR
Troy Asher
Steve Cumming

Agenda

- A brief SOFIA overview
- Review of Open Cavities in Flight
- SOFIA Cavity / Door Design
- Flight Test Approach / Managing Test Points
- Flight Test Results
- SOFIA in Action
- Conclusions and Lessons Learned

Program Objectives

Further scientific knowledge in the field of astronomy and astrophysics by complementing and augmenting ground and space-based observation capabilities through development and operation of a next generation airborne observatory.



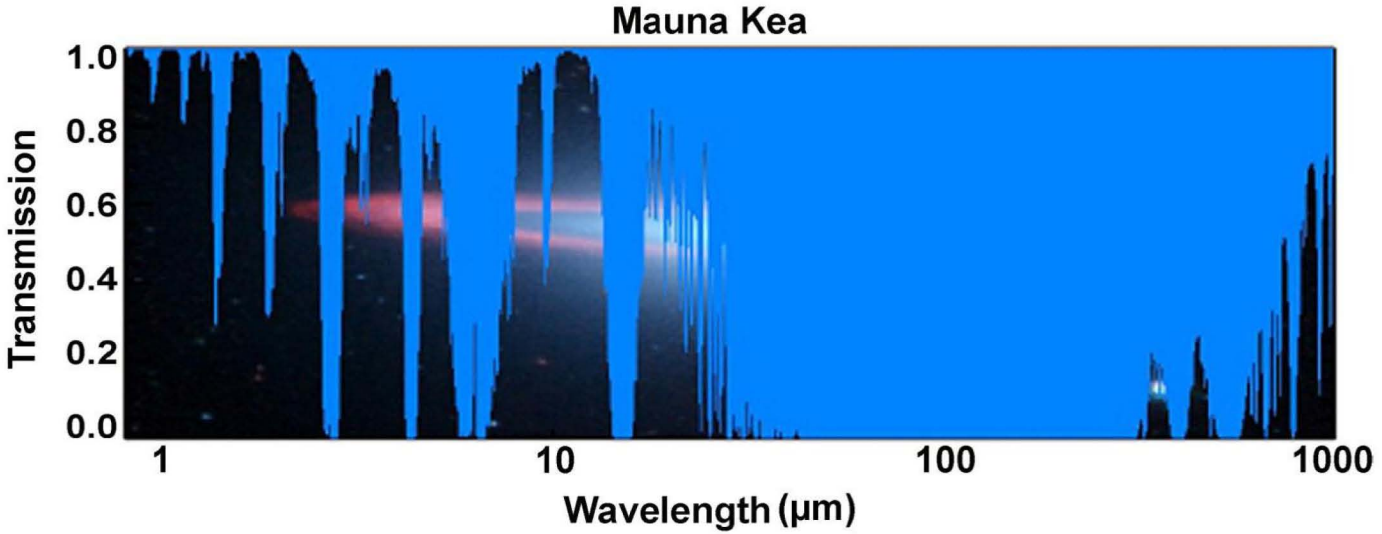
Stratospheric Observatory For Infrared Astronomy

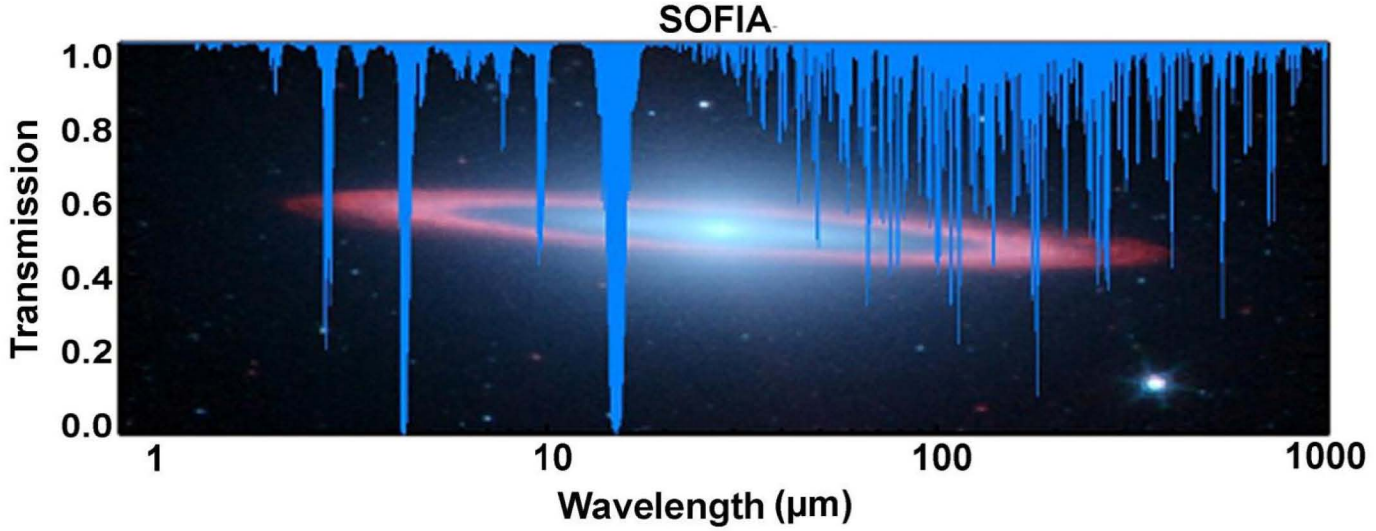
- World's largest flying telescope
- International Cooperative Effort between NASA and DLR
 - Aircraft Ops: NASA Dryden Aircraft Ops Facility, Palmdale, CA
 - Science/Mission Operations
 - NASA Ames Research Center, Moffett Field, CA
 - Universities Space Research Association, Columbia, MD
 - Deutsches SOFIA Institut (DSI), Universität Stuttgart
- Operational lifetime planned for 20+ years
 - Designed to operate at 39,000 to 45,000 feet
 - Above > 99% of obscuring water vapor
 - 7 different scientific instruments, initially; more to follow
- World-wide deployments: 960 science hours per year





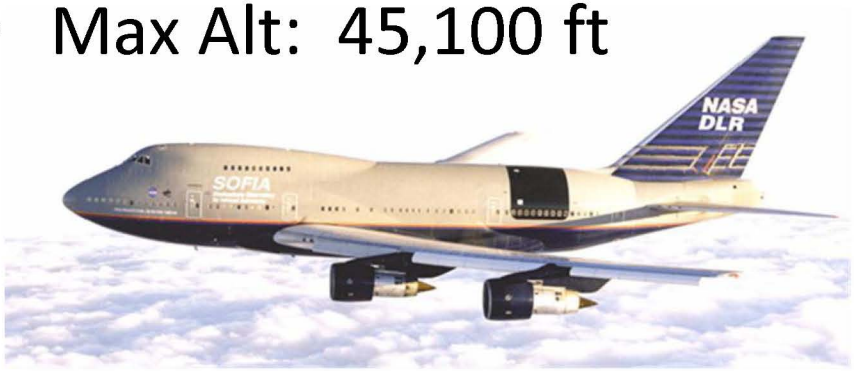
Why Stratospheric?





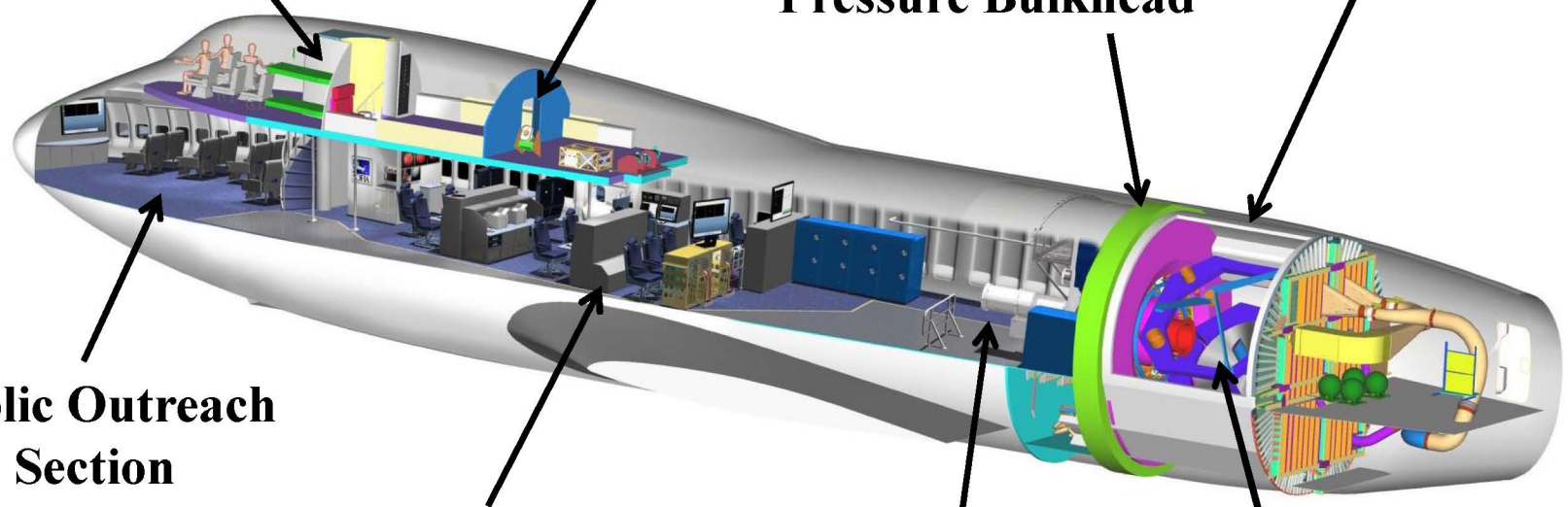
Observatory - The Aircraft

- Boeing 747SP-21 “Clipper Lindbergh”
- Delivered to Pan Am (1977); United Airlines (1986)
- Acquired by NASA in 1997; first flight 2007
- Based at NASA Dryden Aircraft Operations Facility (Site 9), Palmdale, California
- MTOW: 696,000 lbs
- Max Alt: 45,100 ft



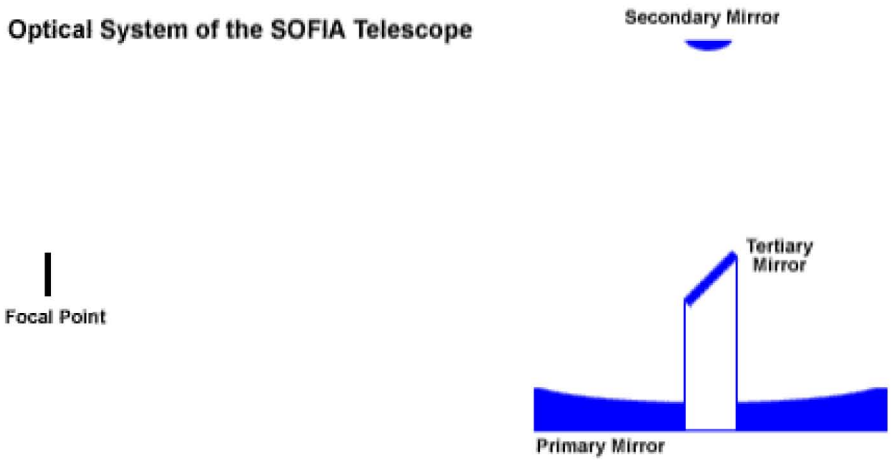


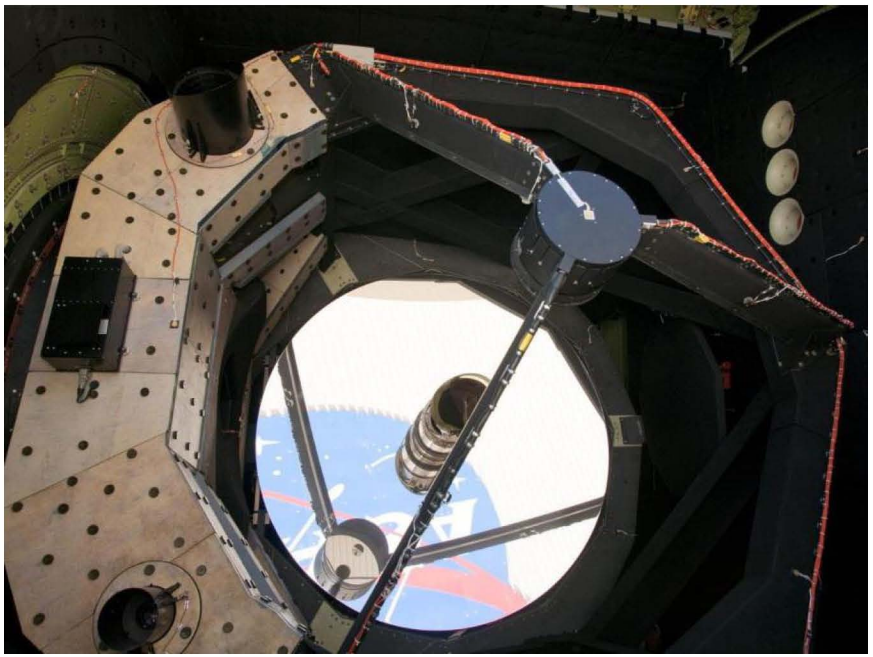
Observatory Layout



Observatory - The Telescope

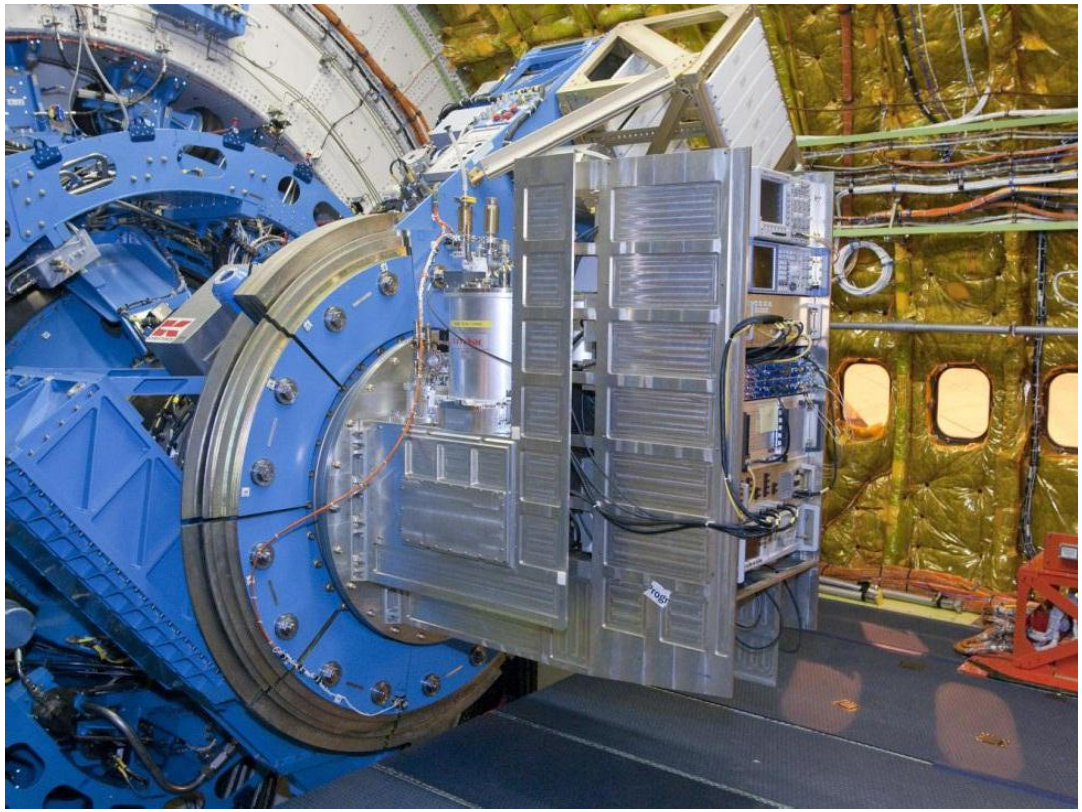
- 2.5m optical/infrared/sub-millimeter
- Built for DLR by MT Aerospace and Kayser-Threde
 - Primary mirror: "Zerodur" glass ceramic from SCHOTT AG
 - Cassegrain Focus in Nasmyth arrangement
 - +15 to +70 degrees above the horizon (full range)
 - Weight: 44,000 lbs/20,000 kg





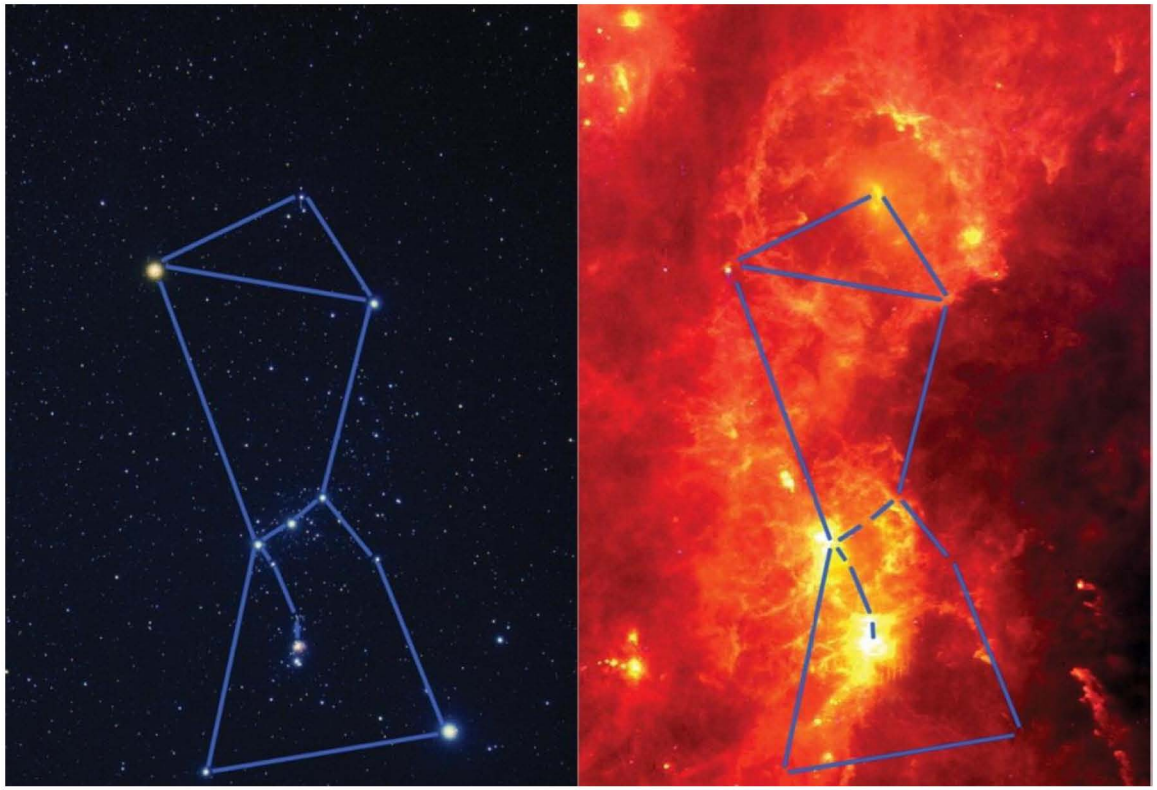
Observatory – Science Instruments

GREAT: German REceiver for Astronomy at Terahertz frequencies spectrometer



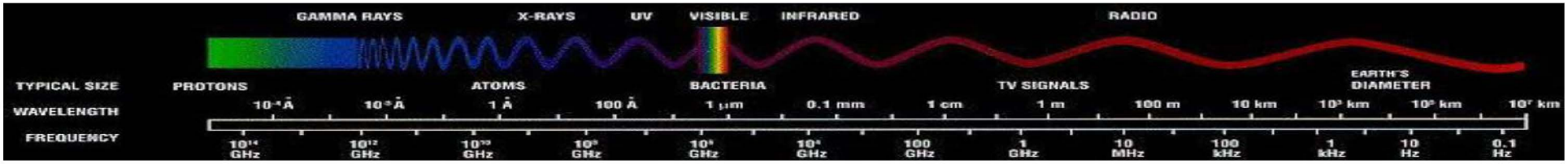
When observing, GREAT will move with the telescope plus or minus 20 degrees from its normal 40-degree angle.

Infrared Astronomy



Orion in Visible Light

Orion in the Infrared



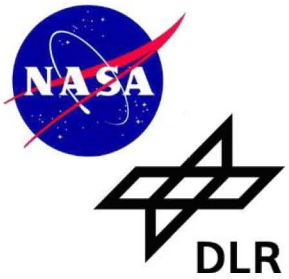
Aerodynmics



Steve Cumming



Flying with Open Cavities



- Flying a large open cavity can be problematic
 - Cavity resonance is common
 - Severe resonance can cause structural damage or fatigue
- Large aircraft cavities often resonate at higher speeds due to Rossiter modes
- The most common solutions to dealing with resonance are an aerodynamic fence, an over-designed structure or flight envelope limitations

History of Large Cavities in Flight











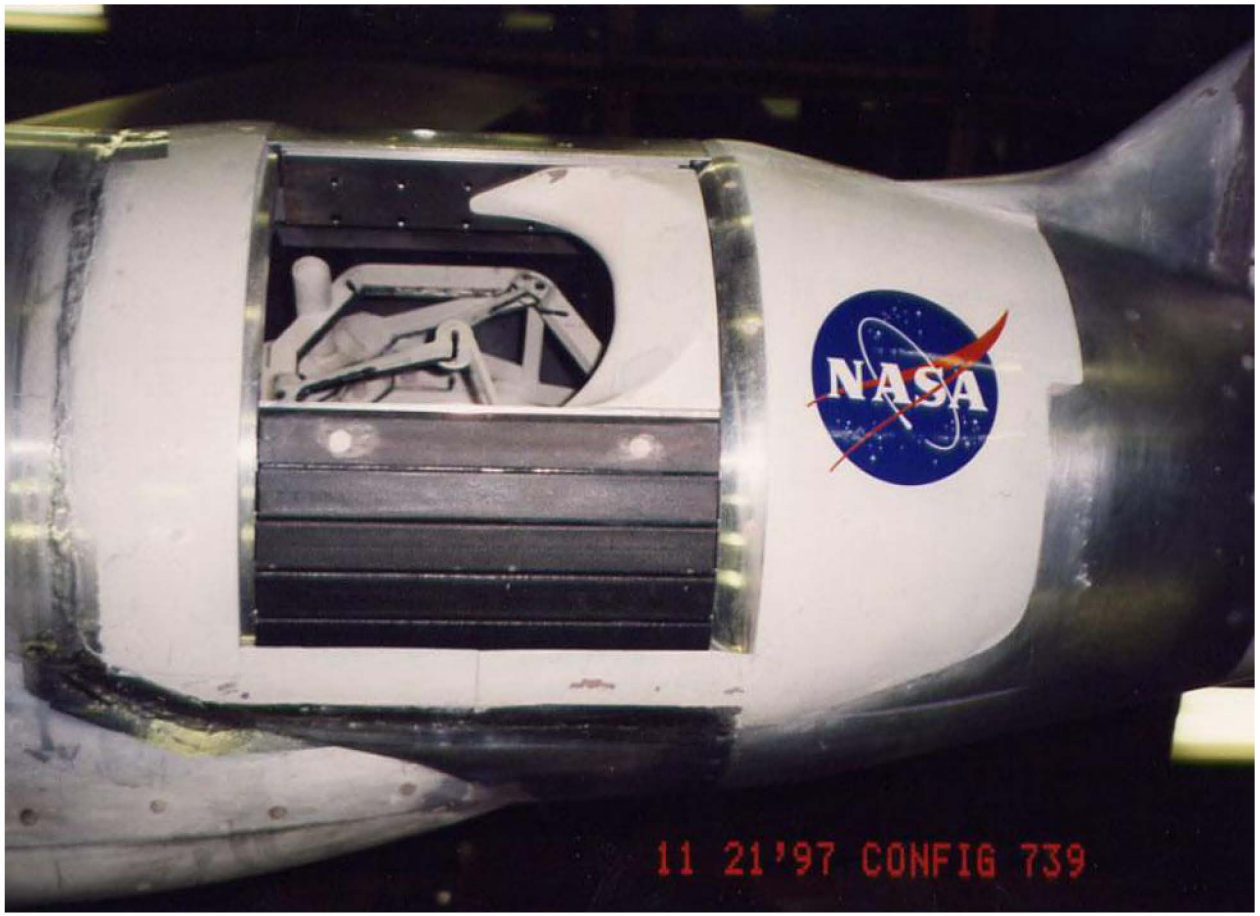
SOFIA Cavity Design

- SOFIA program had several requirements that made commonly used cavity treatments undesirable
 - Provide a platform for observing over a wide range of the EM spectrum
 - Maximize time at-altitude, on-condition
- Plan was to use a shaped cavity and aft ramp to appropriately control the shear layer and minimize the probability of resonance
- To maximize the probability for success a series of wind tunnel tests were undertaken to design the SOFIA cavity
 - Testing began in 1990 and was completed in 1997
 - 5 series of 7% scale wind tunnel tests were completed

SOFIA Wind Tunnel Tests

- SOFIA I
 - Investigated cavity configurations to prevent resonance
 - Established basic flow control design
 - Several 747 variants tested
 - Forward cavity
- SOFIA II
 - 747-200, 747SP variants tested
 - Aft cavity
- SOFIA III:
 - Investigated effects of different TA model designs
- SOFIA IV:
 - Investigated aero-optical properties of candidate configurations
- SOFIA V:
 - Investigated candidate door designs
 - Tested final cavity design and configuration

SOFIA Cavity Design



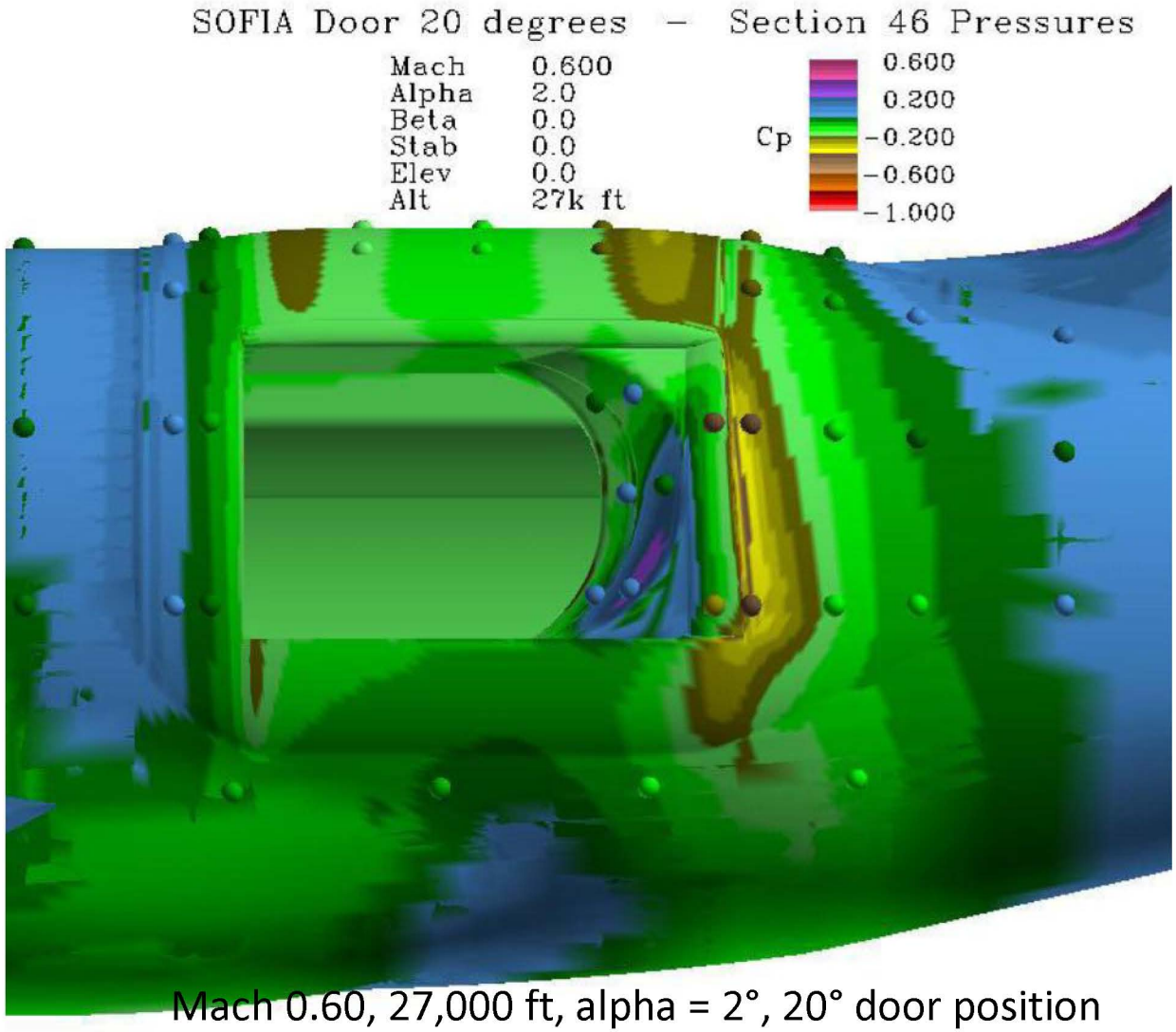
Pre-Flight Analysis and Test

- Substantial testing and analysis was performed prior to SOFIA flight tests
- Aerodynamic and Acoustics tests and analyses:
 - 7% wind tunnel tests
 - 3% wind tunnel tests
 - CFD
 - Baseline flights
 - 6-DOF SOFIA airplane simulation
- Due to the extensive analyses, we had a detailed set of pre-flight predictions for acoustics and possible aerodynamic effects of the cavity

Baseline Flights

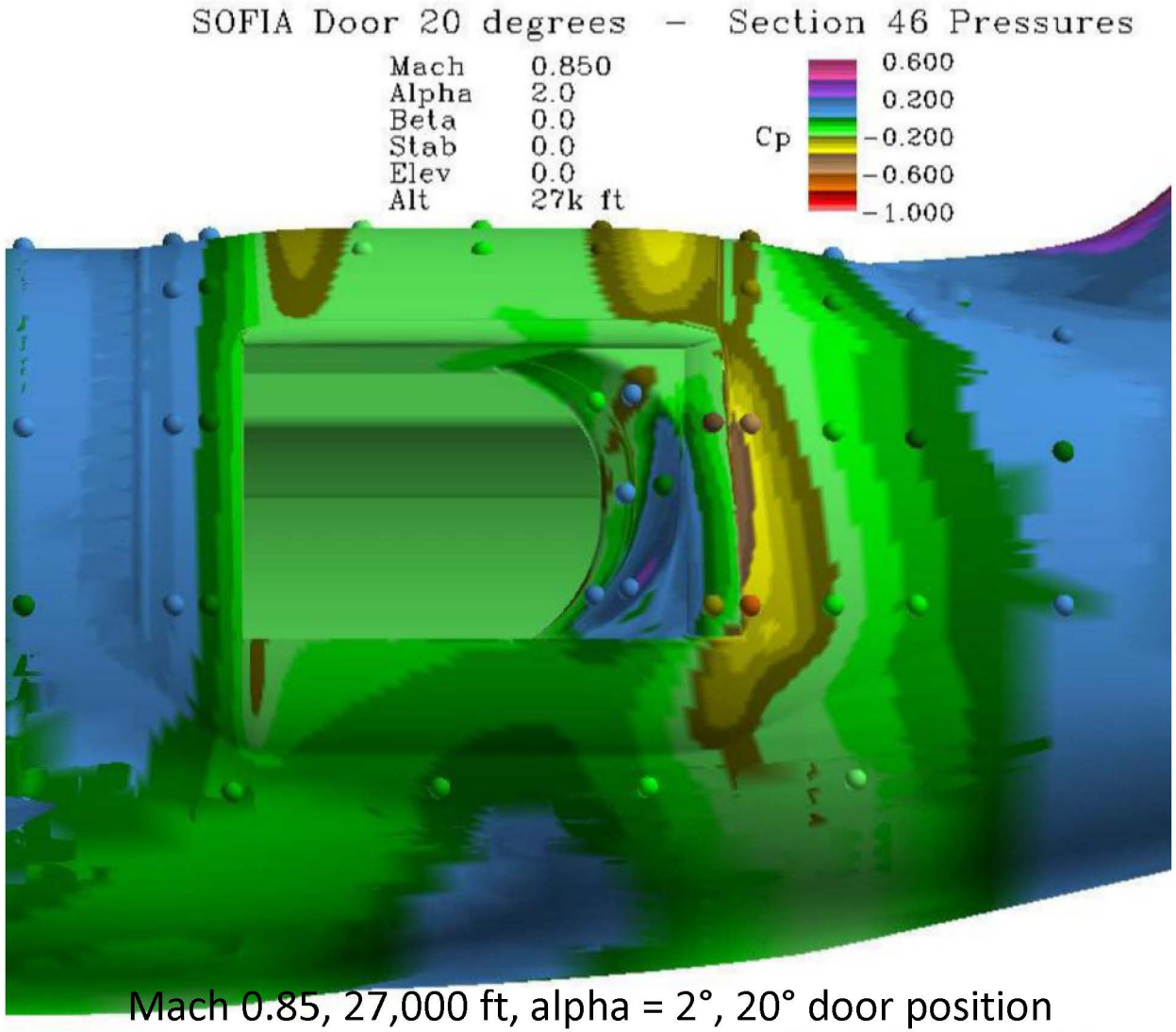


CFD Results



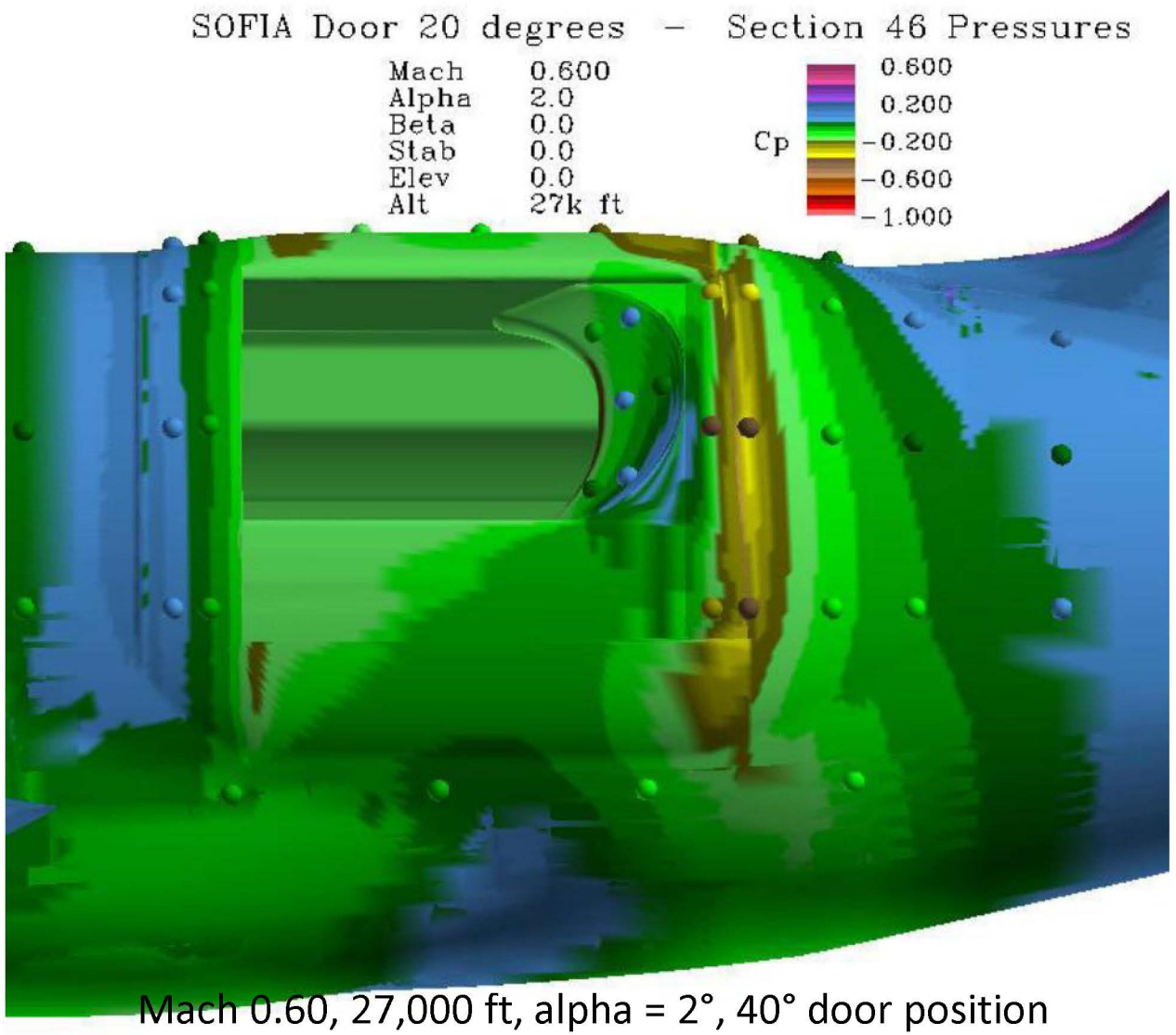
Mach 0.60, 27,000 ft, alpha = 2°, 20° door position

CFD Results



Mach 0.85, 27,000 ft, alpha = 2°, 20° door position

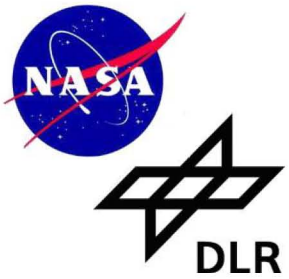
CFD Results



Mach 0.60, 27,000 ft, alpha = 2°, 40° door position

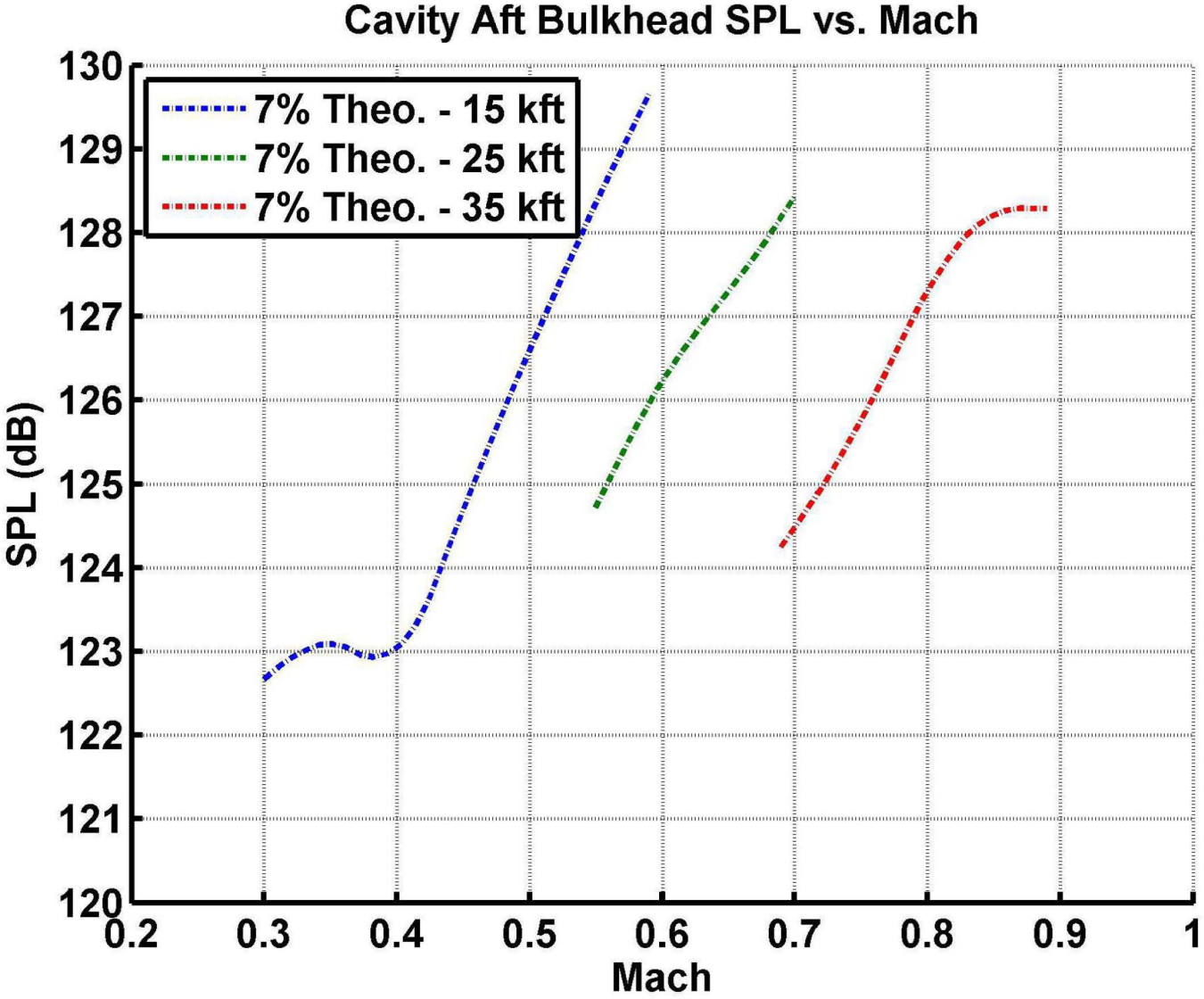


Pre-Flight Predictions

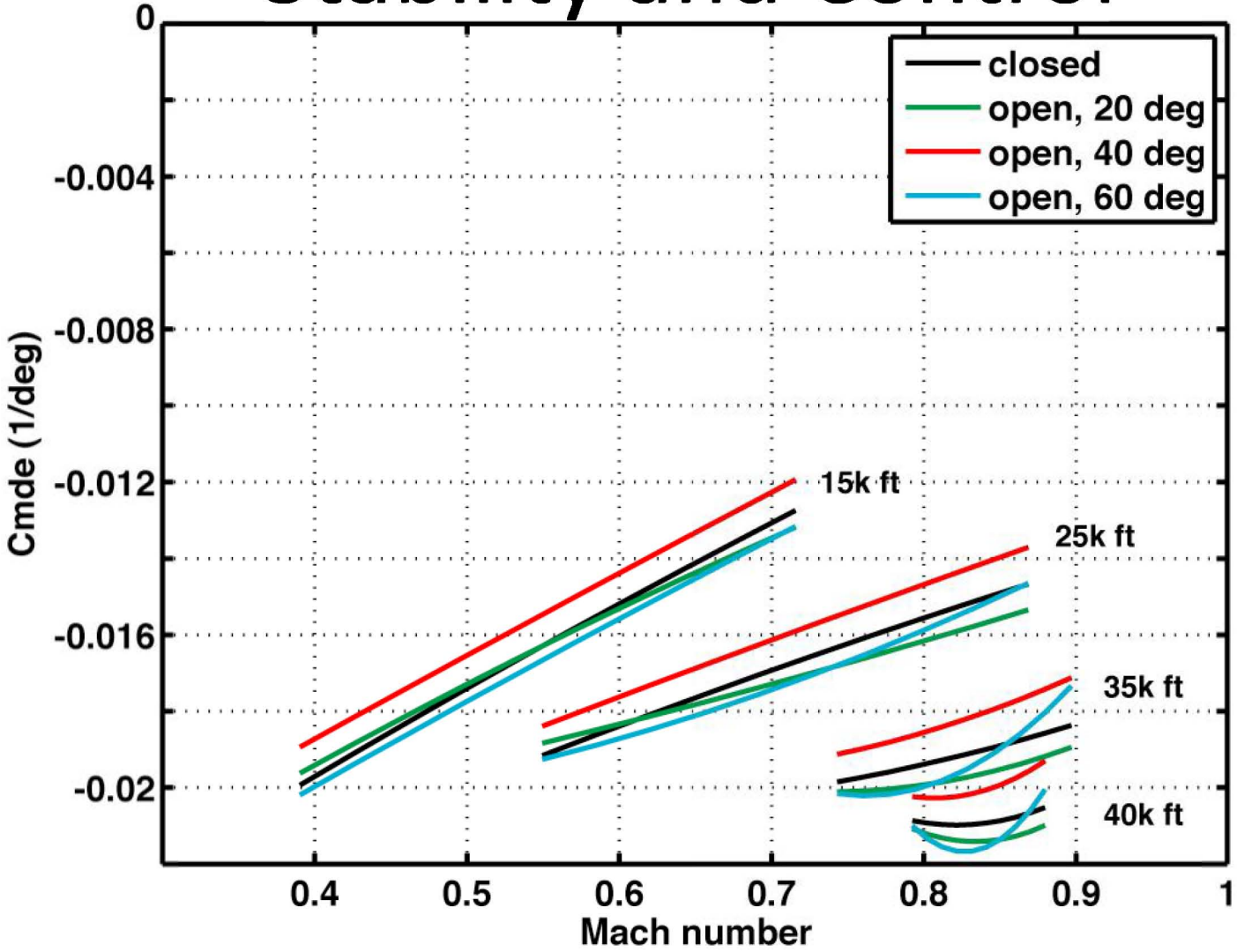


- Predictions for cavity acoustics and stability and control effects were generally positive
- Predicted cavity acoustics were predicted to be well within design range (with some exceptions)
- Predicted stability and control effects due to the cavity were relatively small

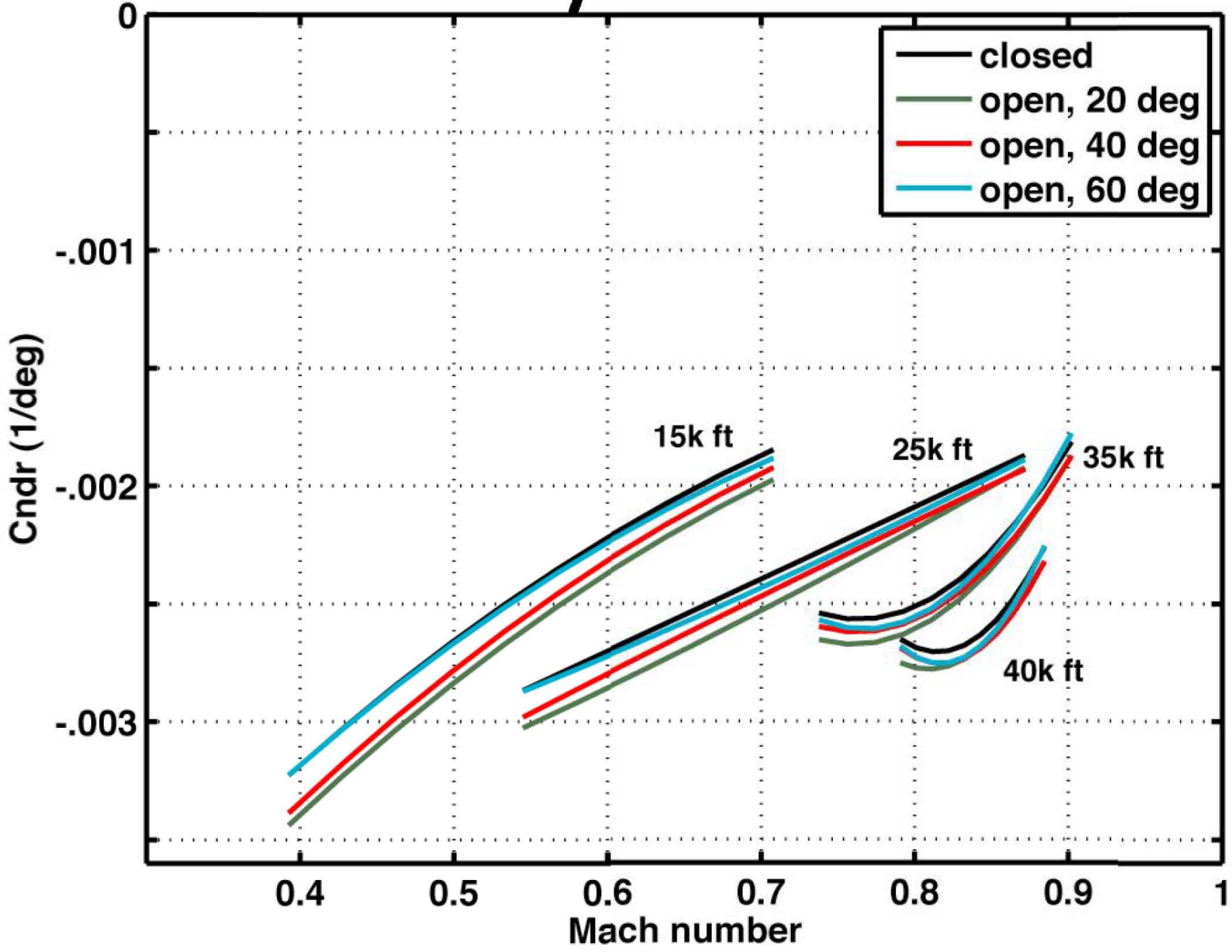
Predicted Cavity Acoustics



Predicted Airplane Stability and Control



Predicted Airplane Stability and Control



Pre-Flight Technical Concerns

- Despite the extensive amount of analysis and test data, there were still serious concerns prior to open door flights:
 - The shear layer control design had not been fully proven outside of wind tunnel tests
 - Scaling issues sometimes make acoustic wind tunnel tests unreliable
 - 3% wind tunnel tests indicated there was a possibility for cavity SPL above limits
 - Predictions for stability and control effects were not considered highly reliable or accurate
 - Some aerodynamic issues, such as possible pitot-static effects were unlikely to be predicted by the available analysis methods

Envelope Expansion Plan

- The set of test points selected for envelope expansion were quite substantial
- Primary drivers for envelope expansion points were acoustics, aerodynamics and S&C
- Large number of test points were driven by a couple key issues:
 - Analysis limitations and blind spots
 - Design of the cavity door system meant that the entire envelope had to be cleared for every configuration

FLIGHT TEST



Troy Asher

Test Plan

- OBJECTIVE: Certify the airplane as a public use aircraft
 - Based on Type Cert. A20WE Rev 41, Mil-Specs, and NASA best practices
 - Additional engineering & science mission requirements
 - Focus was on envelope expansion and certification of the airframe
 - Some effort to show compliance with mission requirements
- PROGRAM GOAL: Clear SOFIA for "Early Science"
 - Short Science: ≥ 35,000 ft MSL and telescope up to 40° elevation
 - Basic Science: > 41,000 ft MSL and telescope full range (58.3°)

Program at risk due to immanent funding loss

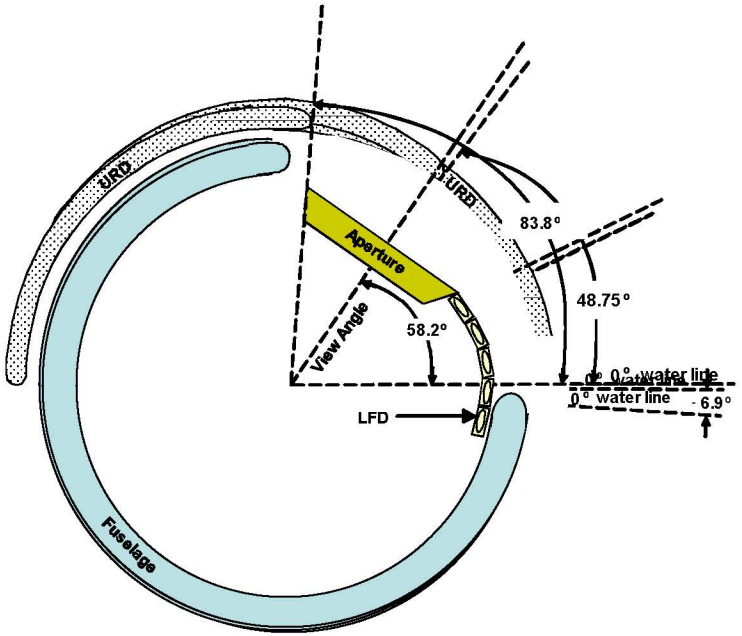
Rigid NASA and DLR HQ Milestones

Test Plan Development

- Airworthiness testing
 - Performance
 - Flying/Handling qualities
 - Model validation
 - Demonstration of satisfactory structural characteristics
 - Flutter
 - Ground Vibration Test (GVT) to validate/update FEM
- Major Test Disciplines involved
 - Aerodynamics (incl. acoustics)
 - Stability & Control
 - Structural Dynamics (Flutter)
 - Static Structures (Loads)
 - Door Drive System
 - Science
 - Operations
 - Telescope

Test Point Selection

- Concentrate on areas not modeled or wind tunnel tested
- Risk of *acoustic resonance* drove check of multiple door/ aperture positions
 - 10%, 40%, 70%, 100% Open – Door could be moved in flight
 - 23°, 30°, 40°, 50°, 58° Aperture – Set prior to flight



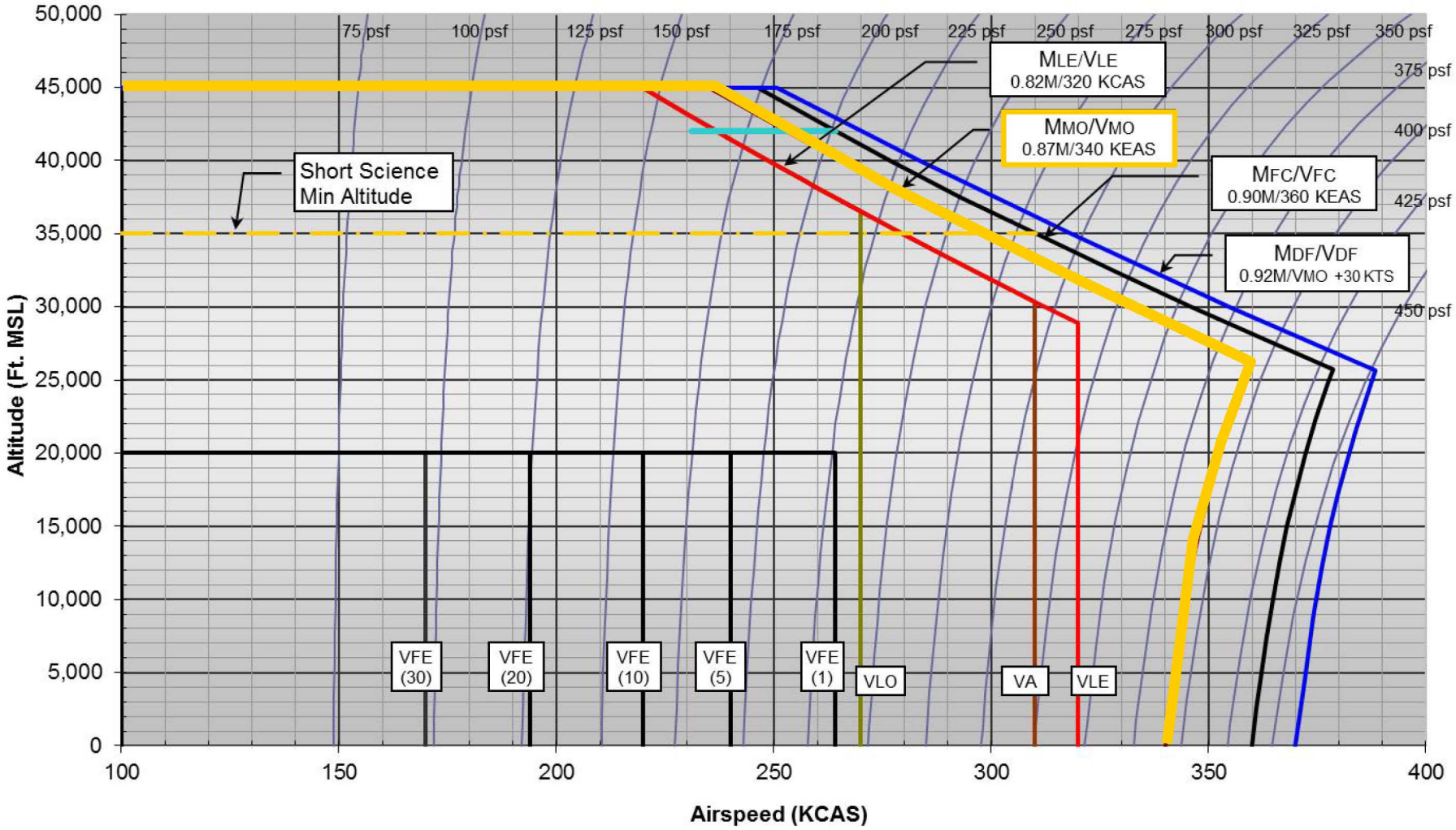
- No data for door open landing configuration
- Include 'Contingency' test points to cover any unknowns

Envelope Expansion
Types of Test Points

Discipline	Type	Maneuver	URD Position
Aerodynamics	Steady State	Trim shot	Closed, open
	Pitot-statics	Accel/decels	Closed, open
		Tower fly-bys	Closed
	FADS Cal	PUPO, rudder sweeps	Closed, open
	PID	Pitch, roll, yaw, yaw-roll doublets, Wind-up turns	Closed, open
	Vibration and buffet	Straight & level flight, maneuvering flight	Closed, open
S&C	Static lat-dir stability	Straight, steady sideslips, V_{mca}, 2-Eng go	Open
Dynamics	Flutter	Raps	Closed, open

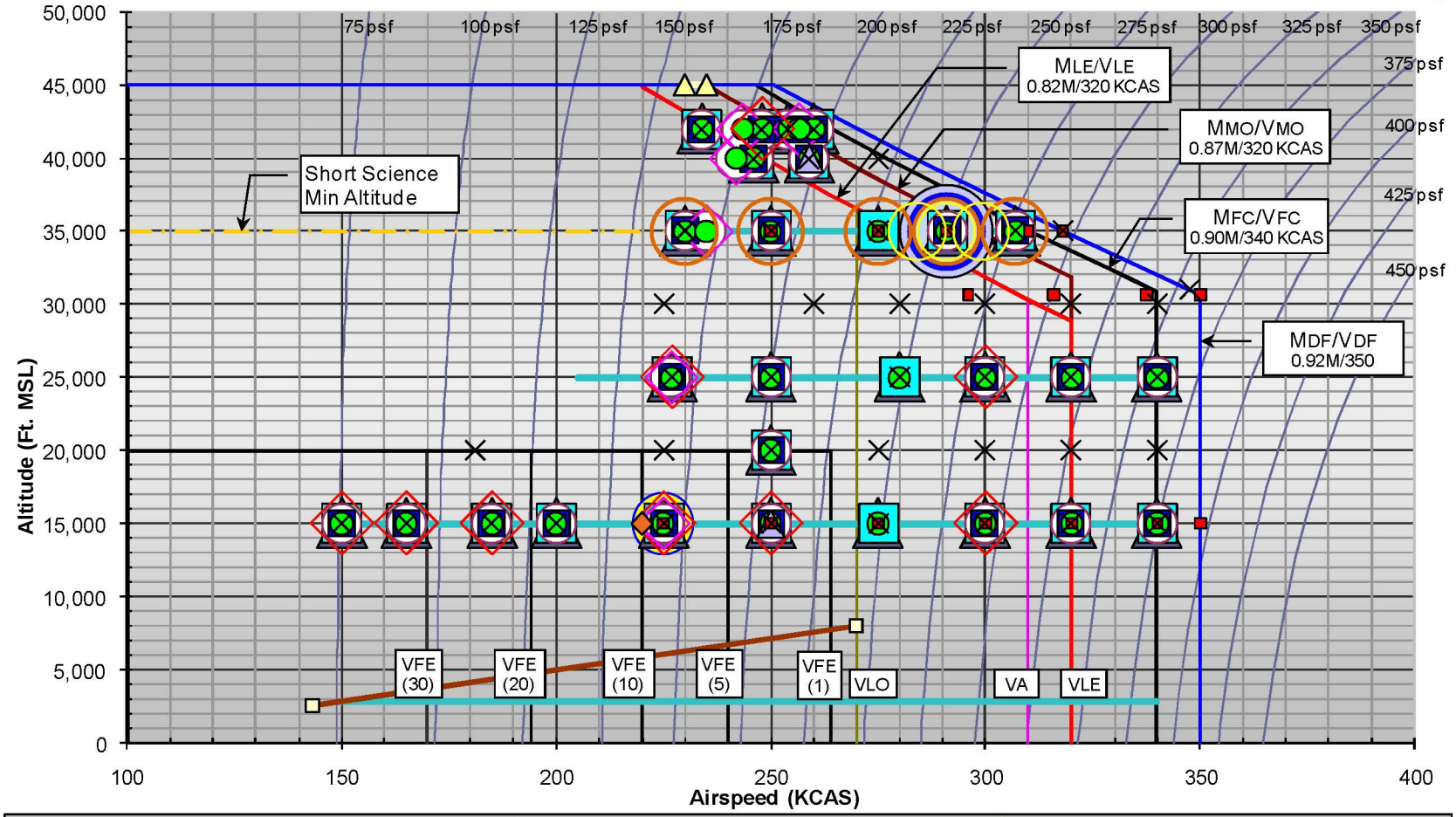
FADS = Flush Air Data System

Initial SOFIA Flight Envelope



V_{DF}/M_{DF} = Maximum demonstrated flight dive speed
V_{FC}/M_{FC} = Maximum airspeed for stability characteristics

Initial Open Door Test Conditions



V_{DF}/M_{DF} = maximum demonstrated flight dive speed

V_{FC}/M_{FC} = maximum airspeed for stability characteristics

Final Test Point Count

	Planned	% Pts
AERO	1474	48%
AERO/S&C	1314	43%
Total Aero	2788	91%
S&C	44	1%
CDDS	2	0.1%
Ops	4	0.1%
Science	6	0.2%
Static Structures	5	0.2%
Struct Dynamics	202	7%
TA	15	0.5%
Test Points	**3067**	**100%**

Challenges

- Primary mirror already installed
 - Sun cover
 - Contamination
 - Thermal conditioning

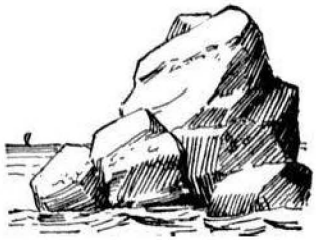


- No test software load
 - Designed to always open door to 100%
 - “Manual Control” for intermediate positions
- Separate flight for each aperture setting
- Instrumentation batteries only good for 6 hours
- “Ride-along” testing for Early Science

Reality Strikes

- "You have too many test points!"
- Defining the problem
 - Milestones: "First Light" & "Initial Science" (ISF)
 - 6 hour flights determine max test points/flight
 - Data analysis/inspections drive fly rate

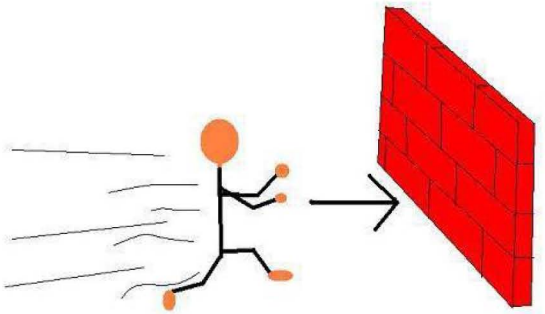
Estimated test capacity: 1000 test points



Fly Rate

Test Effectiveness

Reduce Test Points



Milestones

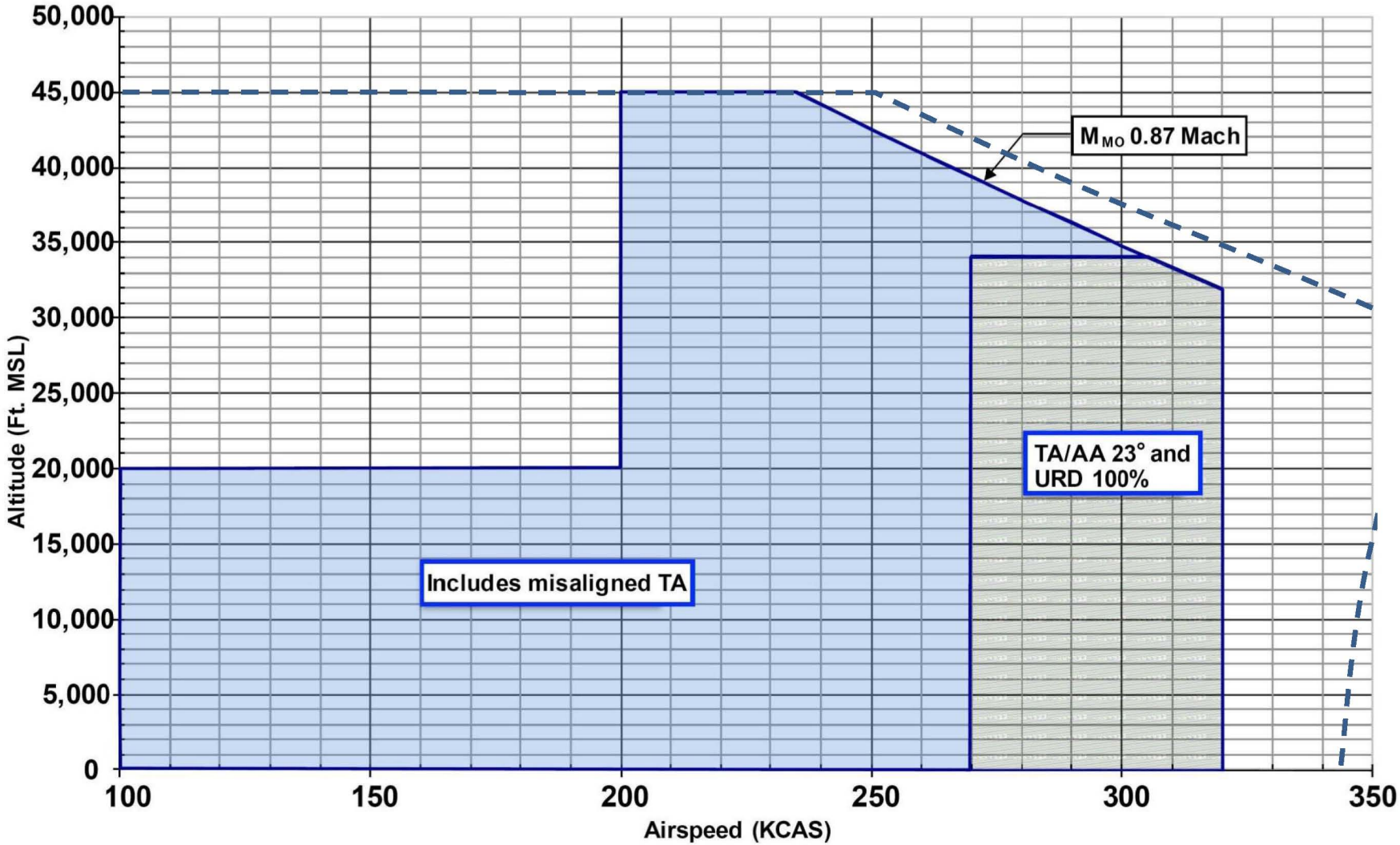
The Approach

- **"Schedule for Success" but plan for the worst**
- Optimistic assumptions vs. flight test results
 - Assume best-case technical results from flight test
 - If test results validate models, skip ahead but spot check
 - Fly 23° aperture at all test conditions
 - Fly 40° aperture at a reduced set of test conditions
 - Go back and spot check 30° aperture



- Publish a "Success Oriented" Schedule, BUT
- If any optimistic assumptions are inaccurate, more test points will be flown to investigate…schedule will slip
- Not all optimistic assumptions expected to be accurate

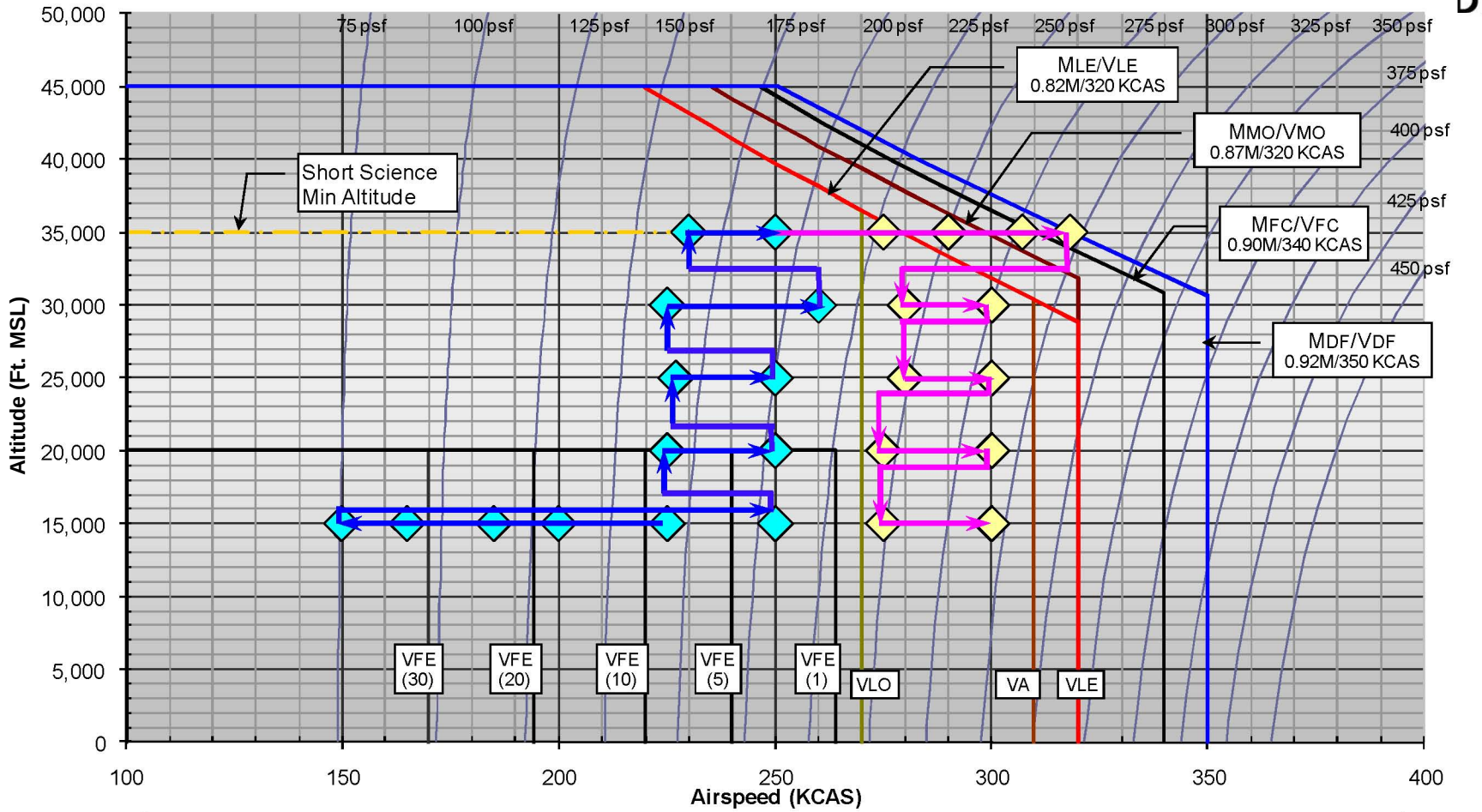
Reduced Airspeed Envelope



DER Recommendations

- Consulted with FAA Designated Engineering Representatives on adequacy of test plan
 - 15 items suggested for deletion from test plan
 - 9 items suggested to add to test plan
 - Majority of suggestions encorporated

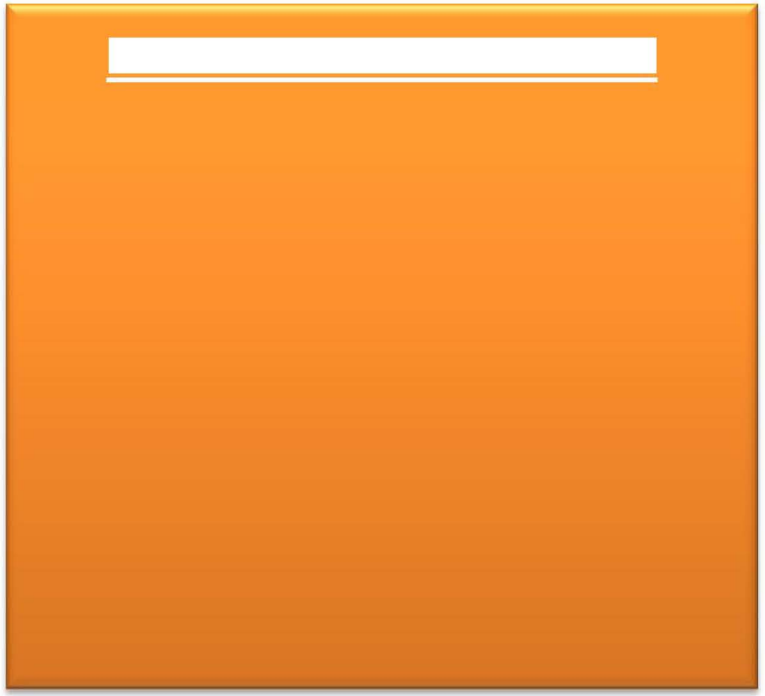
Open Door Envelope Expansion Approach



V_{DF}/M_{DF} = maximum demonstrated flight dive speed
V_{FC}/M_{FC} = maximum airspeed for stability characteristics

Test Point Sequence

- Clear Aero, Acoustics, S&C and Flutter I.T.B.s
- Performance, buffet boundary and systems
- Open Door Landing
 - Plan one open door landing in worst-case configuration
 - No wind tunnel or analytical data for ground effect case
 - KAO had an unexpected acoustic event during flight test in the landing flare

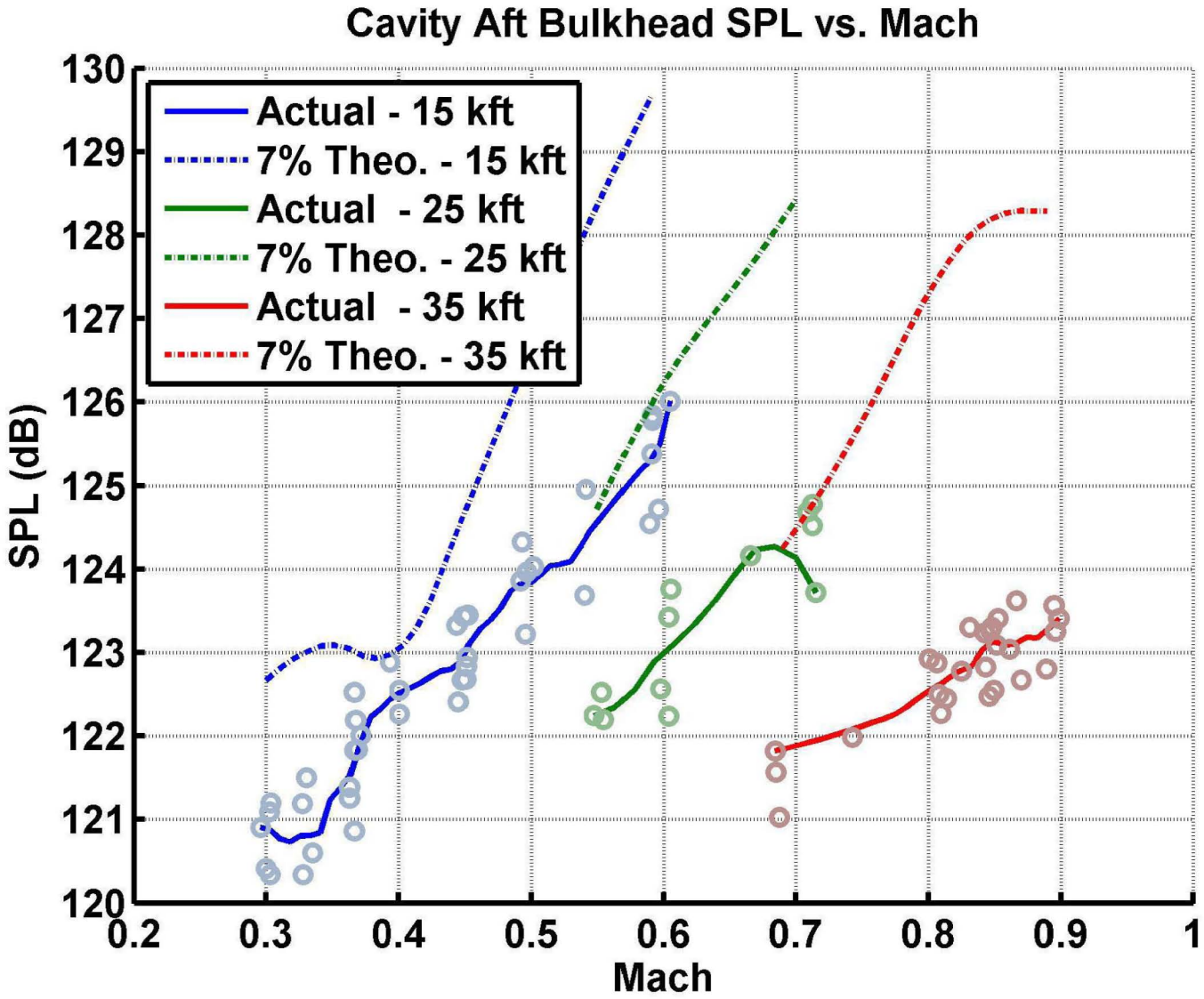


Flight Test Results

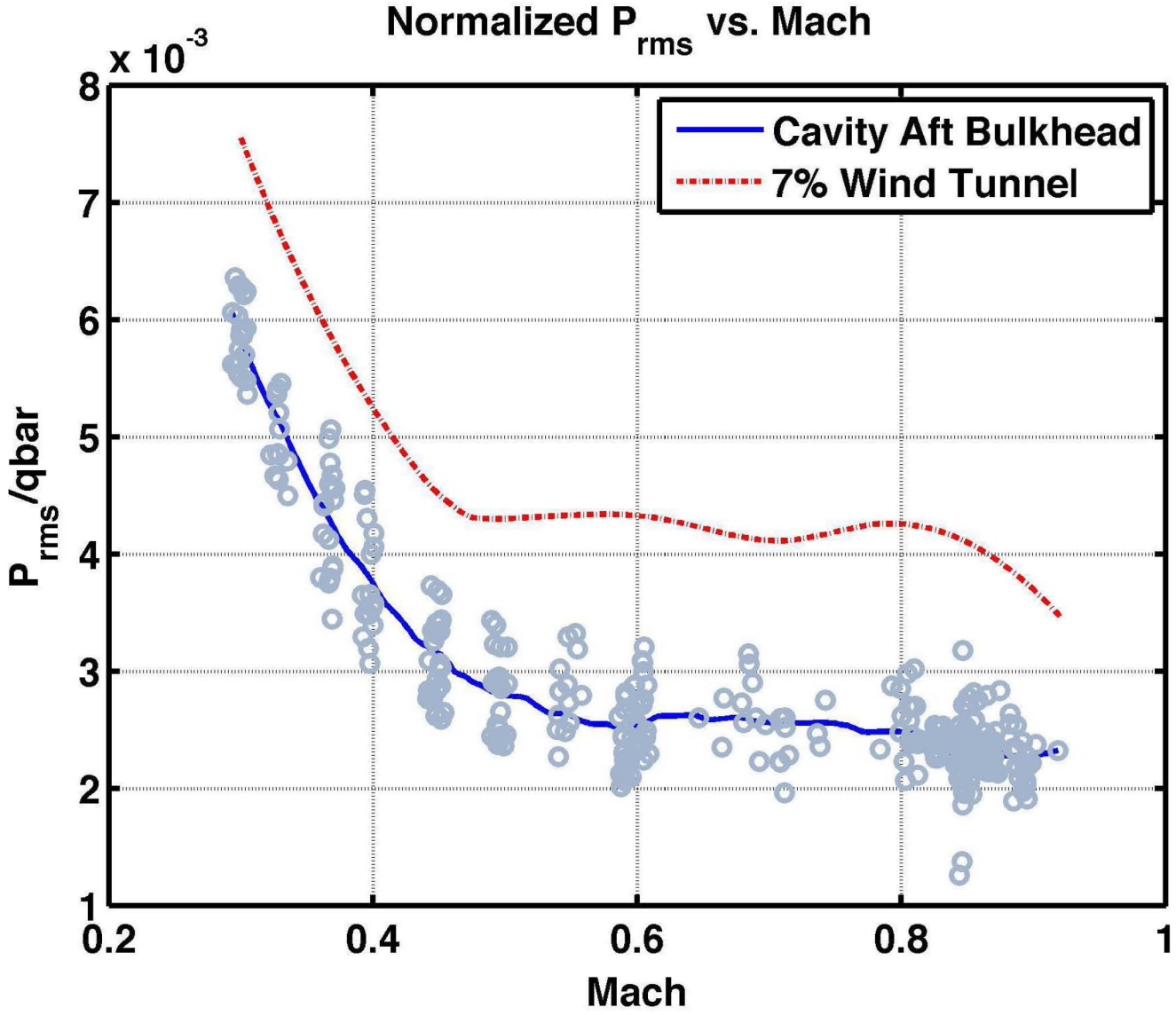
- Final results exceeded expectations
- Found NO substantial or consistent effects on stability and control
- Sound pressure levels in the cavity were below expected values
- Handling qualities not degraded
- Flies like a stock 747



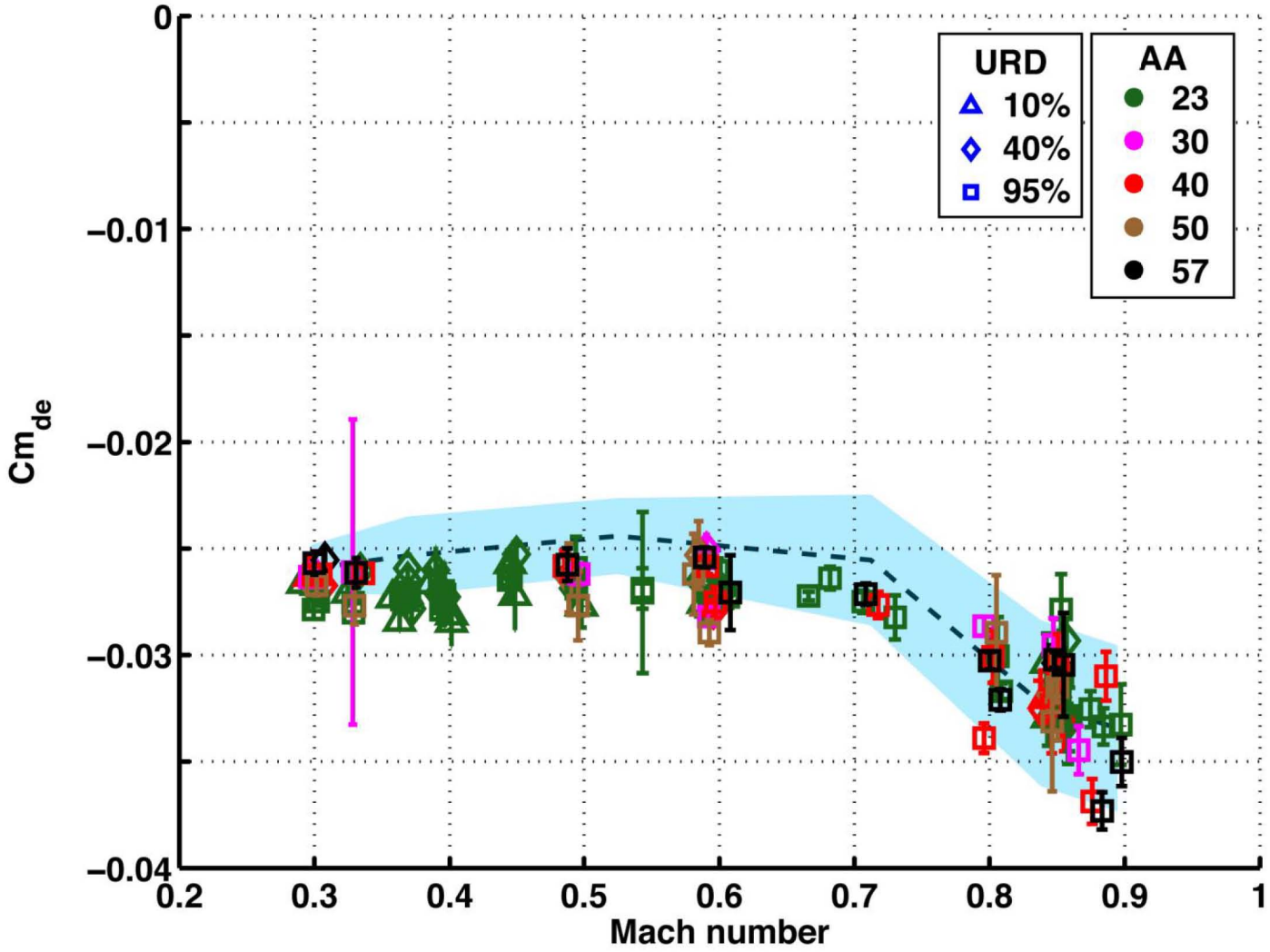
Cavity Acoustics



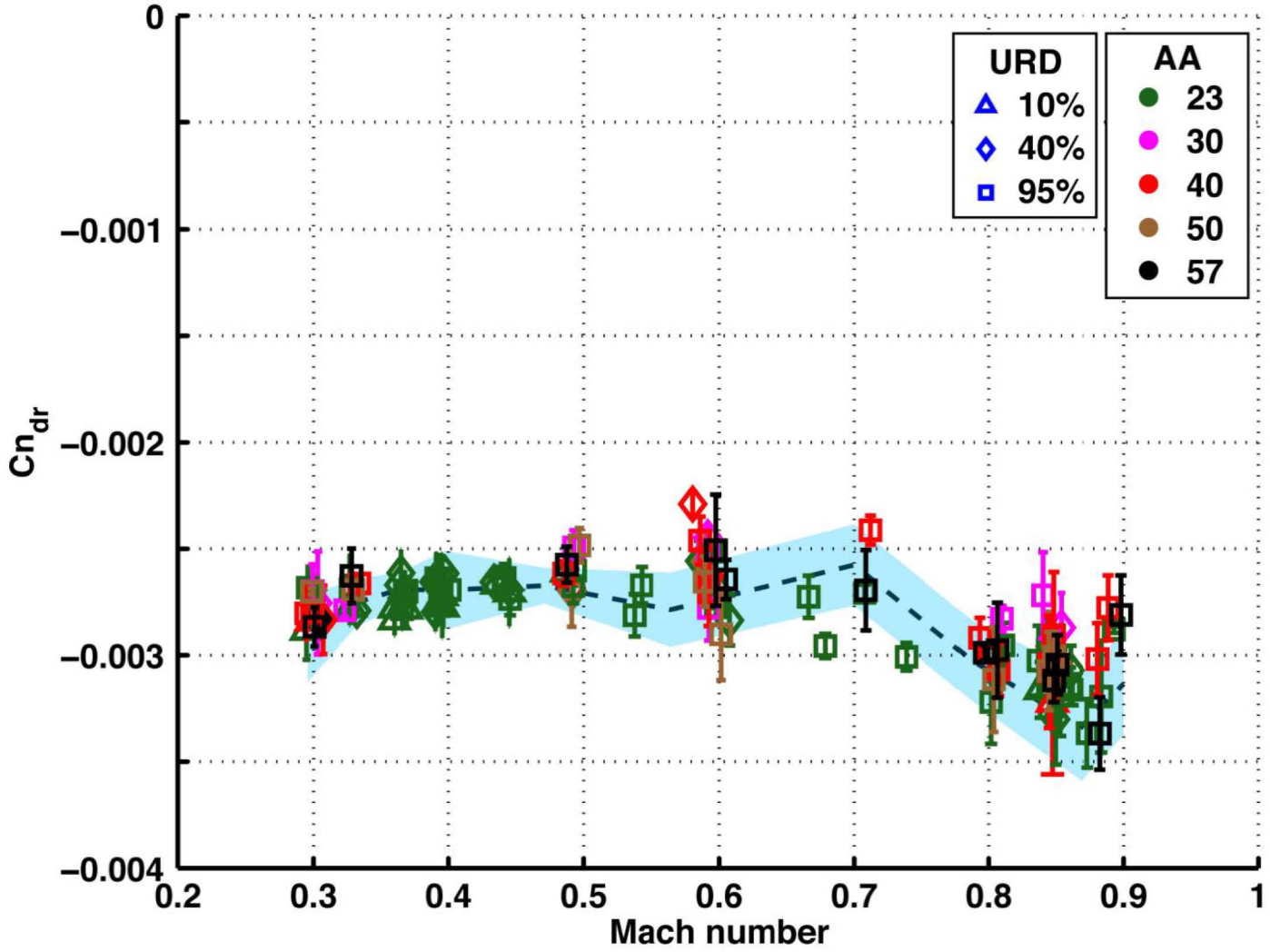
Cavity Acoustics



Stability and Control Results



Stability and Control Results





- G-overshoots during Wind-up turns
- Steady-heading-sideslips at low speed
- Stuck door landings

First 100% Door Open



Final Score

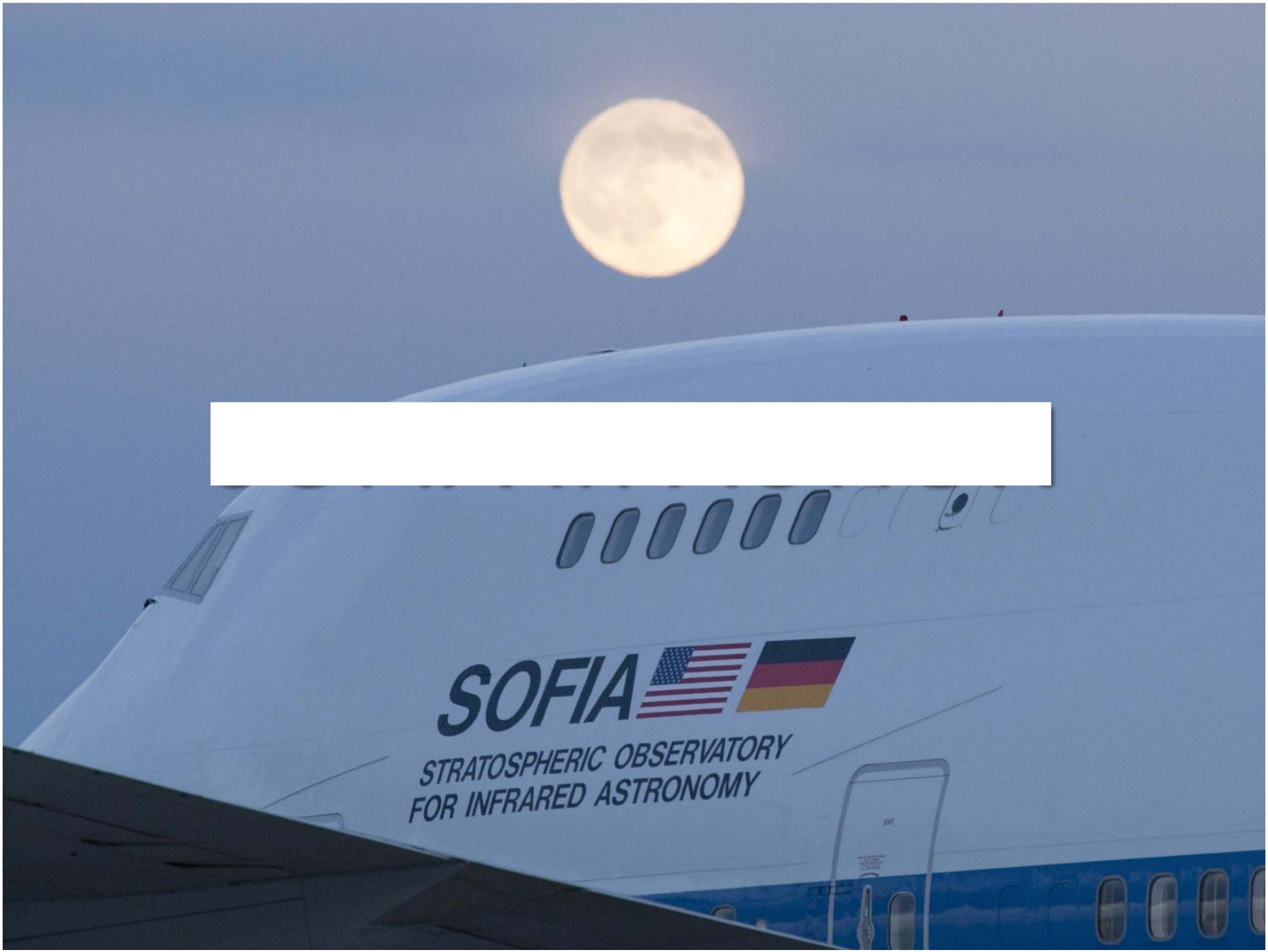
	Planned	% Pts	Flown	Saved	% Redux
AERO	1474	48%	478	996	68%
AERO/S&C	1314	43%	309	1005	76%
Total Aero	2788	91%	787	2001	72%
S&C	44	1%	31	13	30%
CDDS	2	0.1%	2	0	0%
Ops	4	0.1%	4	0	0%
Science	6	0.2%	6	0	0%
Static Structures	5	0.2%	5	0	0%
Struct Dynamics	202	7%	16	186	92%
TA	15	0.5%	14	1	7%
Test Points	3067	100%	865	2202	72%

The Most Common Question

- Q: What do you feel when the door opens?

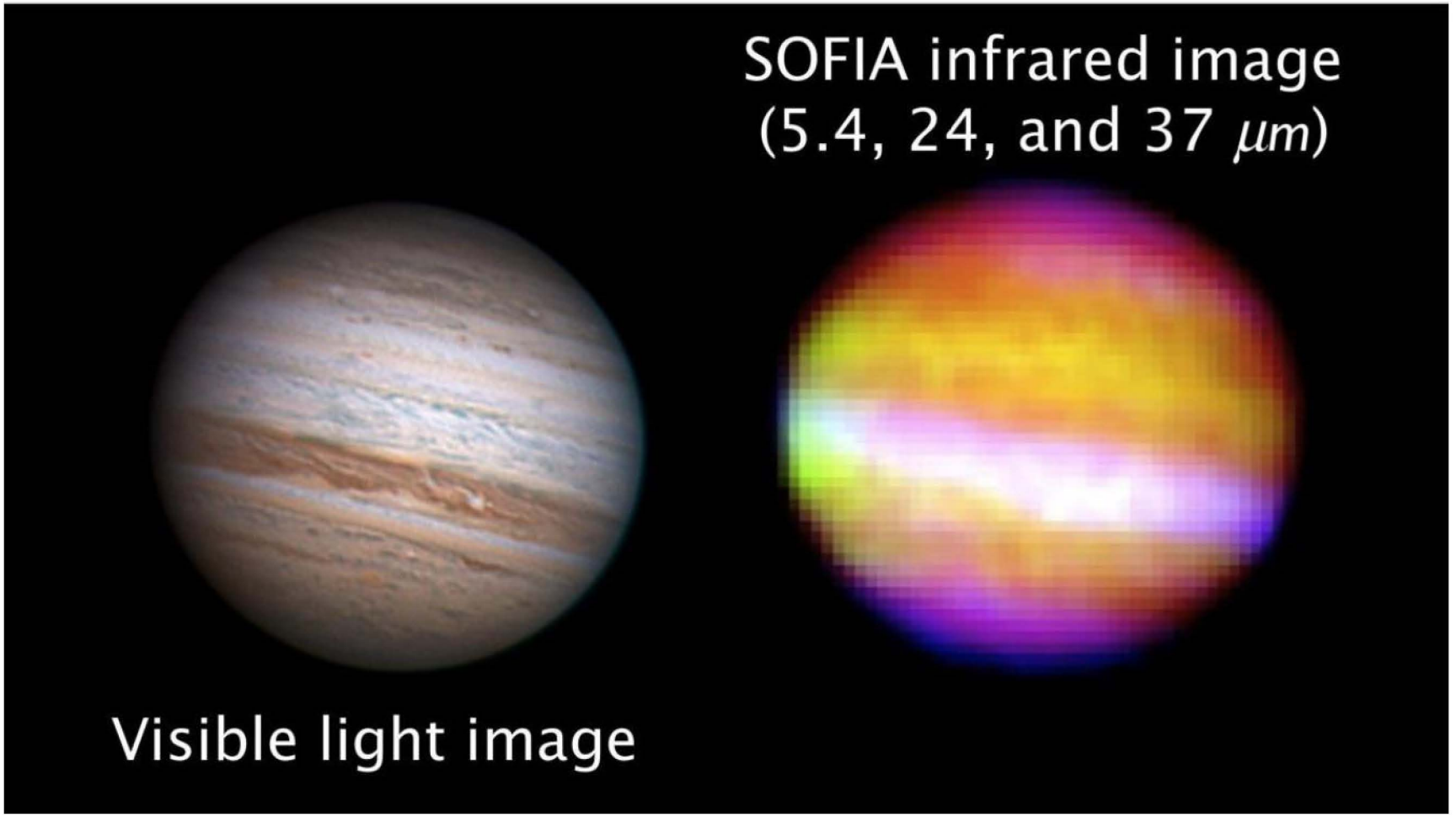
- A: NOTHING!

 If you didn't know the door was open through instrumentation and systems operating, you wouldn't even notice it.


SOFIA
STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTRONOMY

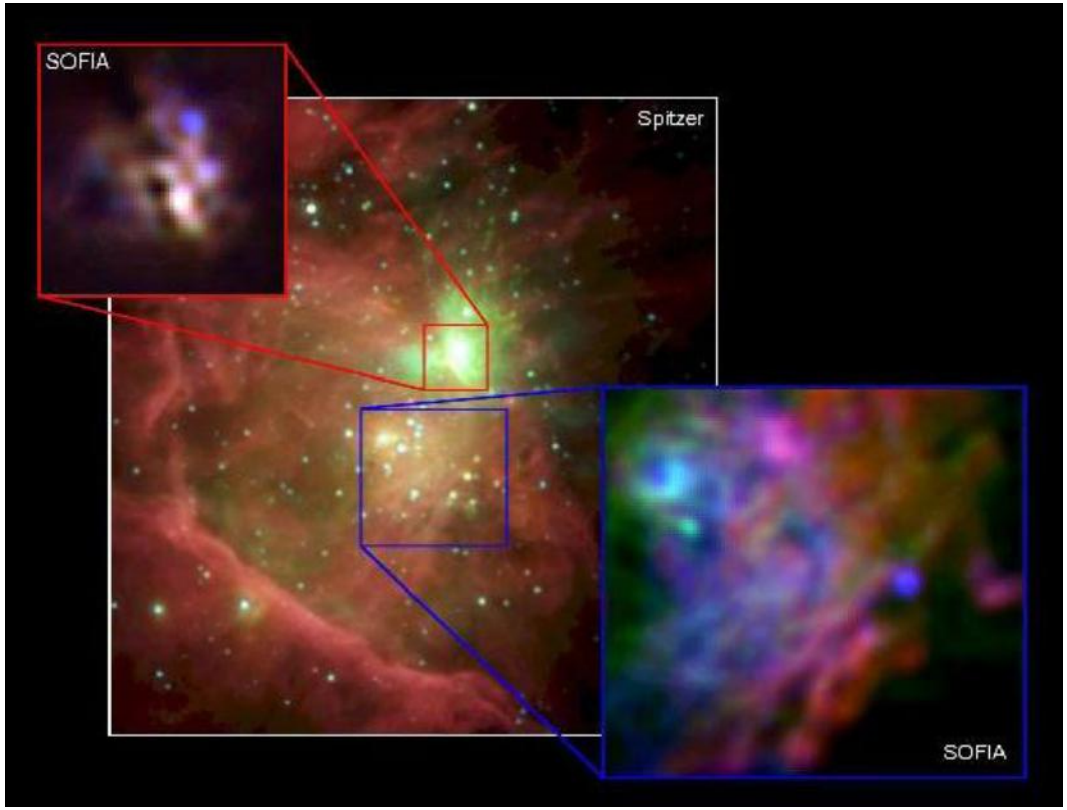
“First Light” Image of Jupiter

May, 2010



Images from SOFIA

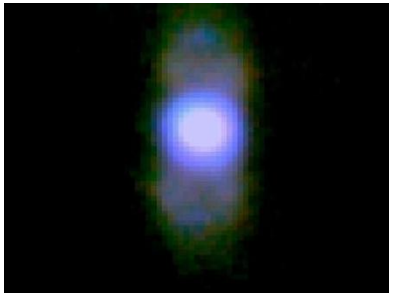
Heart of Orion Nebula



Graphical representation comparing two infrared images of the heart of the Orion nebula captured by the FORCAST camera on SOFIA with a wider image of the same area from the Spitzer space telescope.

SOFIA image -- James De Buizer / NASA / DLR / USRA / DSI / FORCAST; Spitzer image -- NASA/JPL

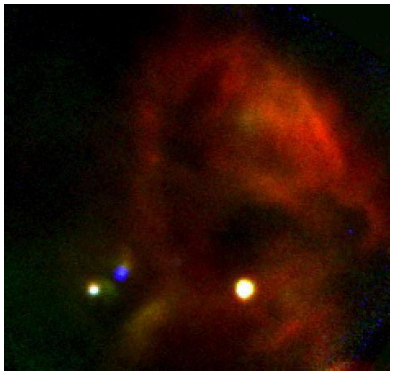
Planetary Nebula M2-9



The last exhalations of a dying star

June 2011, NASA/DLR/USRA/ DSI/FORCAST team/M. Werner, J. Rho

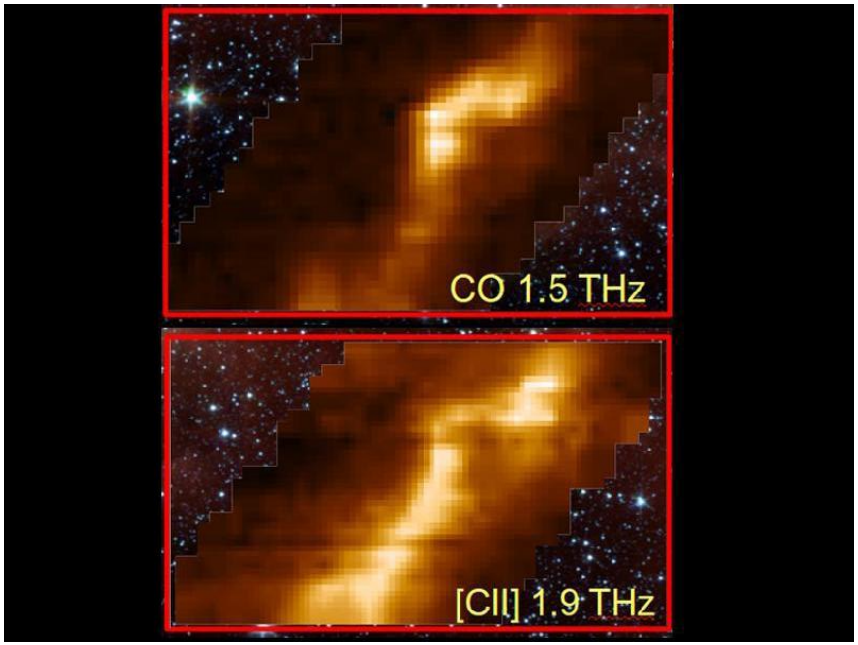
W40



Mid-infrared image of the W40 star-forming region of the Milky Way captured by FORCAST

NASA / FORCAST image, May 18, 2011

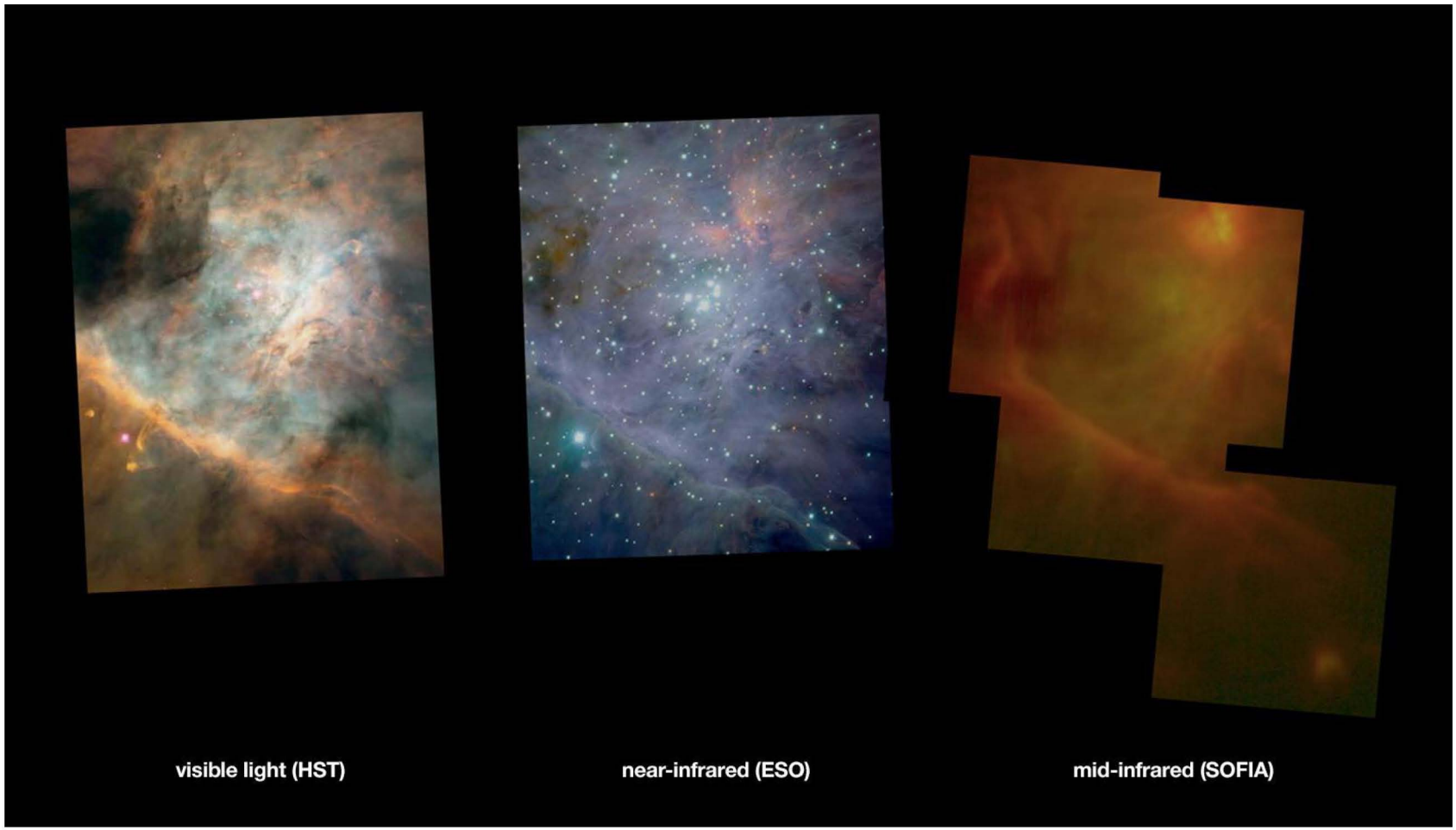
GREAT



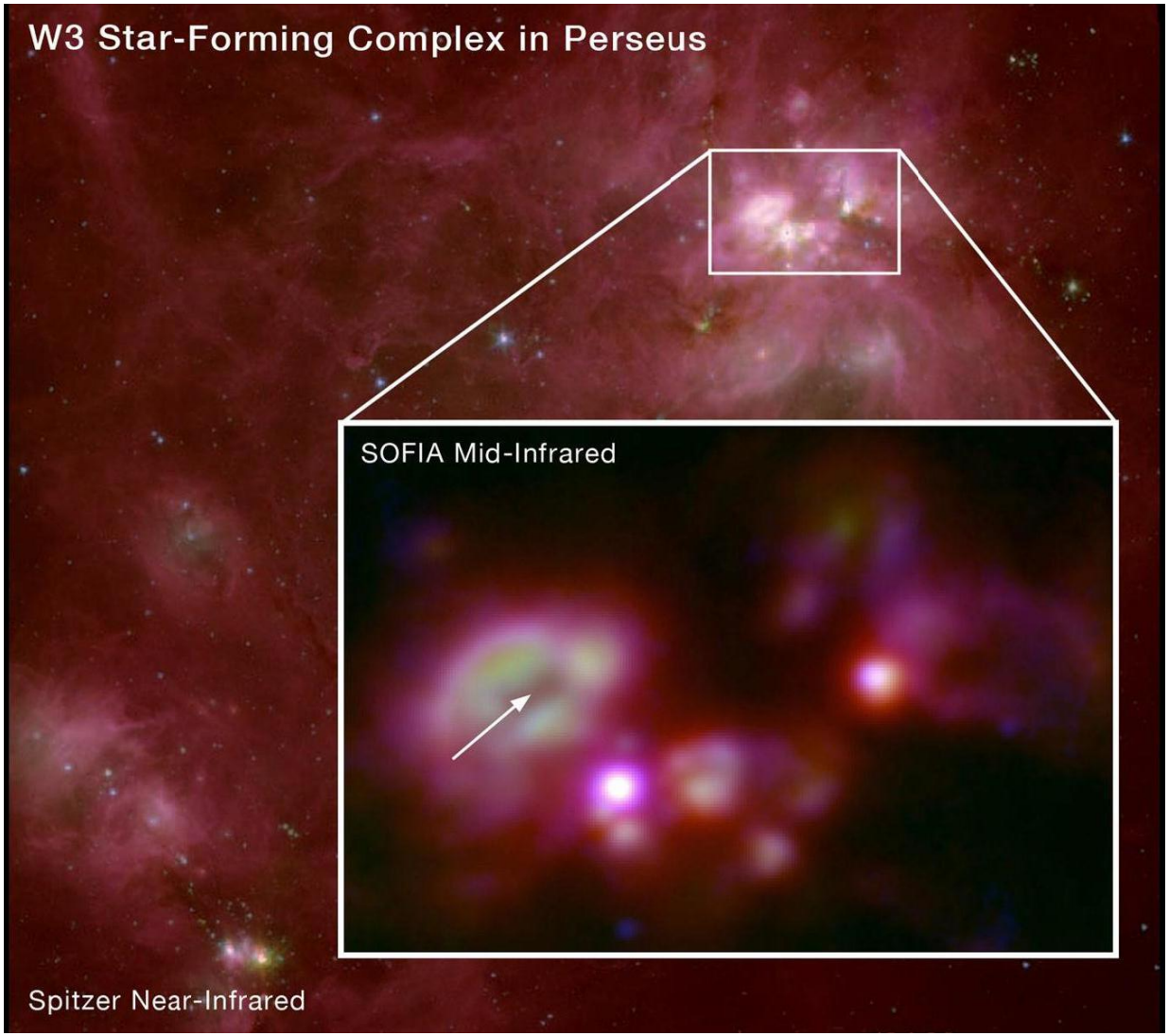
- GREAT collected its first THz photons from the M173W star forming cloud April 6, 2011. Superimposed on a near-infrared false-color image measured by the Spitzer Space Telescope are selected spectra of ionized carbon (CII) and warm carbon monoxide (CO). The high spectral resolution of GREAT is used to study the velocity structure across the cloud.

April 6, 2011 (GREAT Team/NASA/DLR/USRA/DSI)

Mid-IR image of Orion Messier 42 Star-forming Region



W3 Star-forming Region



Mid-infrared image of the W3A star cluster (inset) captured by FORCAST in 2011. Image overlaid on a near-infrared image from the Spitzer space telescope. The SOFIA image scale is 150x100 arcseconds and the red, green and blue colors represent 37, 20 and 7 µm. The red, green and blue colors in the background image from Spitzer represent 7.9, 4.5, 3.6 µm.

SOFIA image: NASA / DLR / USRA / DSI / FORCAST team Spitzer image: NASA / Caltech - JPL. 2011

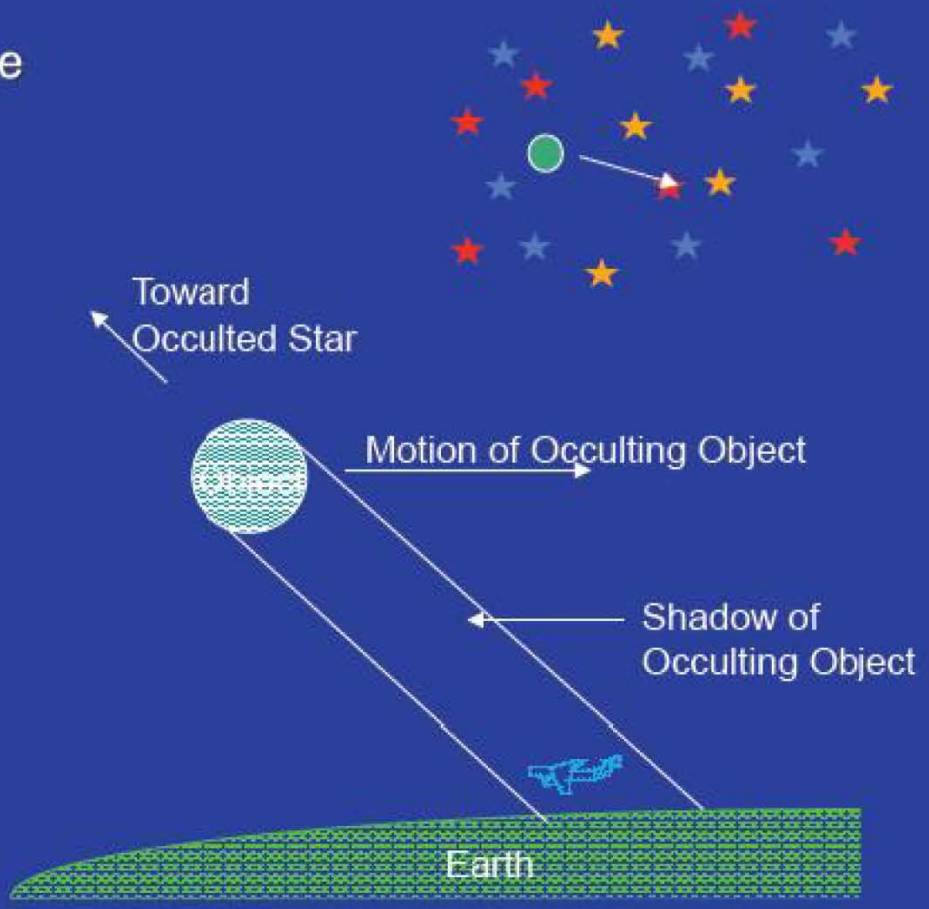
Stellar Occultation by Pluto

- Proof of Concept: First test of a 'time sensitive' operation
- Observational Objectives
 - Observe Occultation Central Flash
 - Observe Pluto lightcurve at high SNR
 - Observe Pluto/Charon joint occultations
 - Observe Pluto/Star separated photometry with HIPO
- Science Objectives
 - Measure Atmospheric Asymmetry (wind distortion?)
 - Measure Atmospheric Profile (Pressure/Temp vs. Alt)
 - Measure Atmospheric Size (Rising trend reversing?)
 - Identify Pluto Ephemeris Errors (Future events and New Horizons)
- Operations Objectives
 - Safely fly a very long mission and return to Palmdale
 - WHAT ABOUT A STUCK DOOR??

Planetary Science; Occultations

SOFIA is able to:

- Go anywhere on Earth to reach the occultation shadow of an object
- Can probe the sizes, structures (rings & moons), and atmospheres of solar system bodies by measuring how they occult background stars
- This will be the primary objective for HIPO (High-speed Imaging Photometer for Occultations)



Returning to PMD with open door

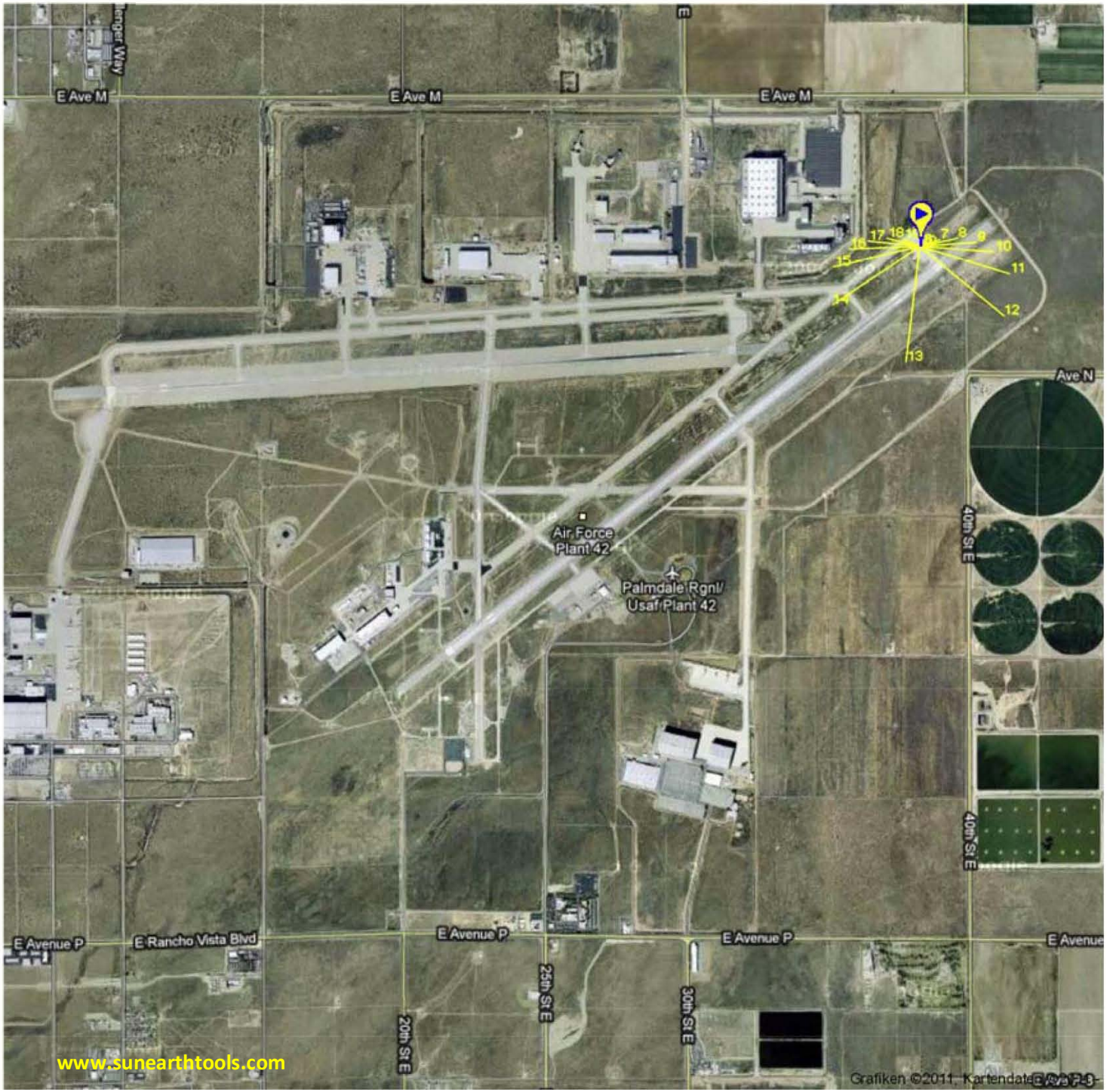
True headings back to Palmdale from the URD decision point are:

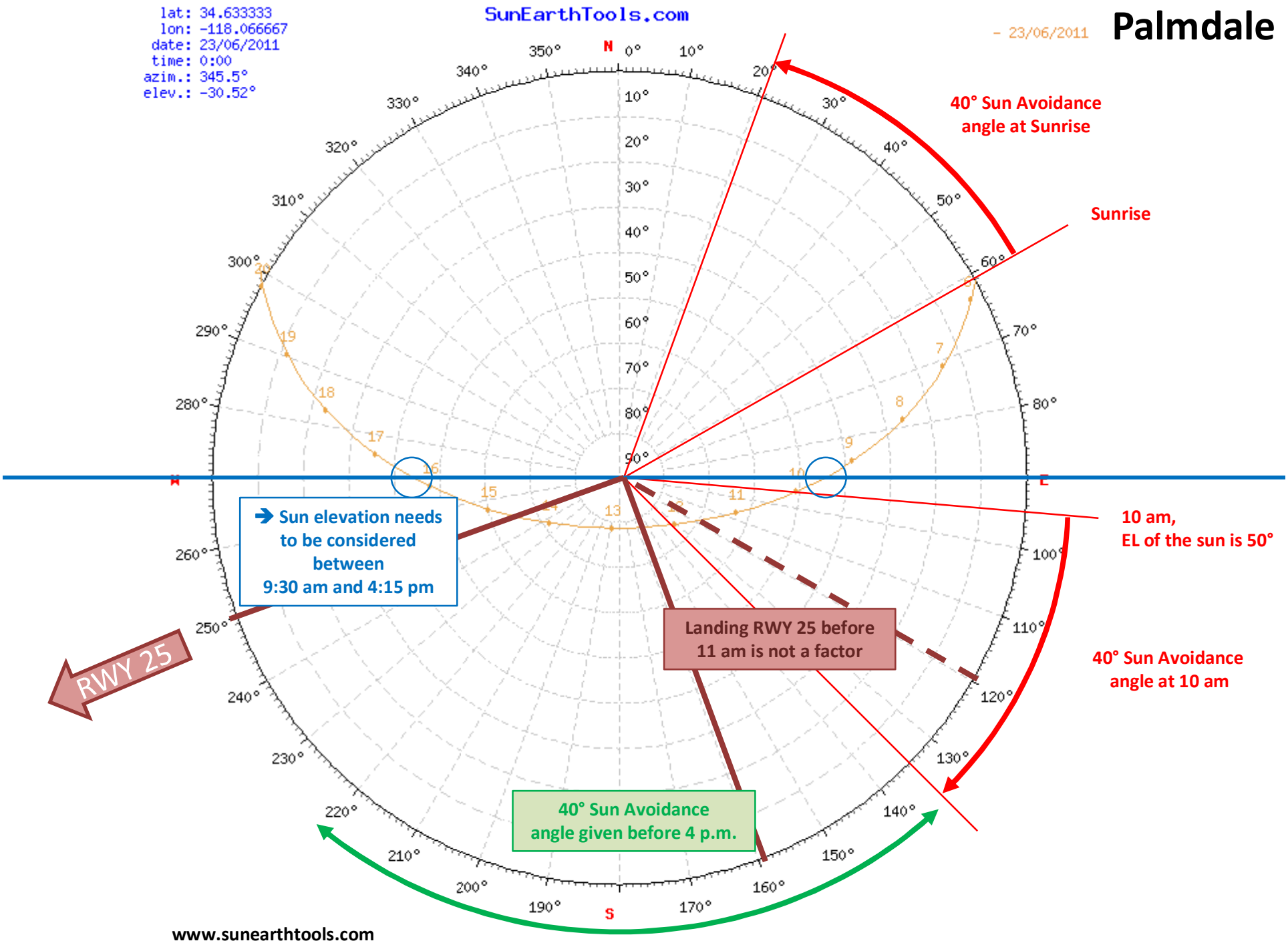
a) default flight plan 23° to 26°

b) alternative flight plan 28° to 32°

➔ No in-flight concern with catching sunlight, because TA is facing north-west

Palmdale

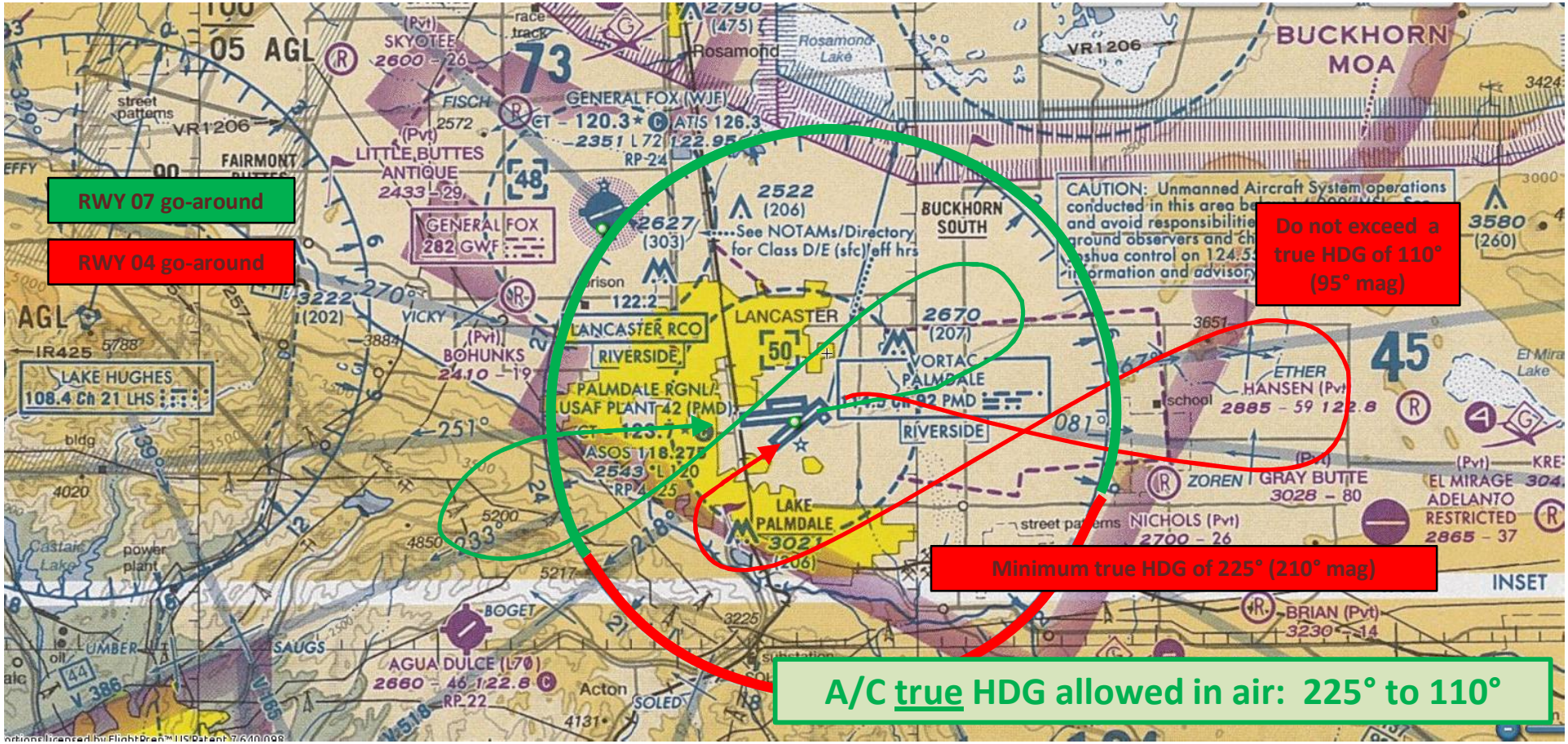

E Ave M
E Ave M
E Ave M
Air Force Plant 42
Palmdale Rgnl/ Usaf Plant 42
Ave N
40th St E
40th St E
E Avenue P
E Rancho Vista Blvd
E Avenue P
E Avenue P
E Avenue
20th St E
25th St E
30th St E
www.sunearthtools.com
Grafiken ©2011, Kartendaten ©2011



www.sunearthtools.com

Pilot’s in-flight short reference card (6)

In case of a Go-around in PMD only a ‘figure 8’ pattern is possible to reposition to a suitable runway



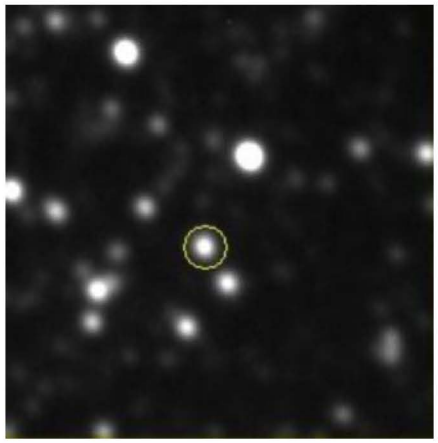
Stellar Occultation by Pluto

July 23, 2011

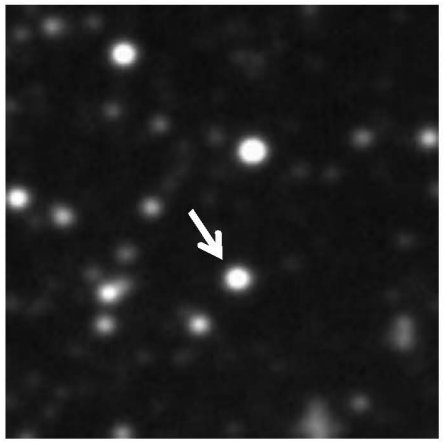
- Dwarf planet Pluto (V~14) occulted a star (V~14.4)
- SOFIA met the shadow of Pluto in mid-Pacific
- HIPO (Lowell Obs.) and FDC (DSI) instruments observed the occultation simultaneously



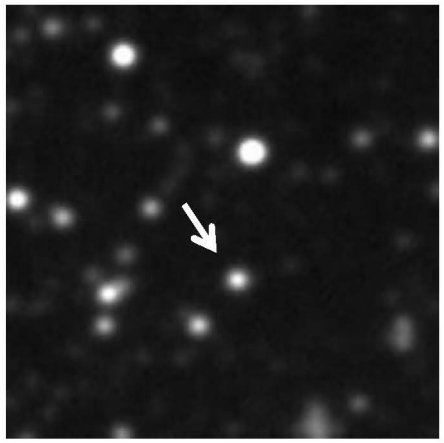
Image sequence from the Fast Diagnostic Camera (FDC)



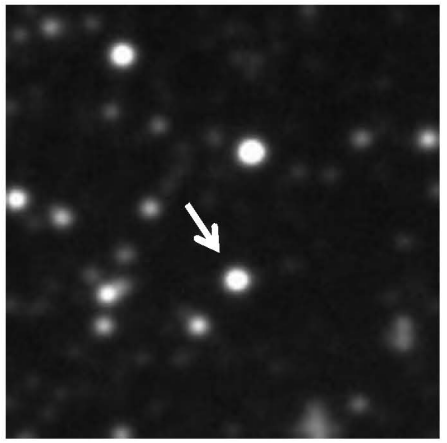
Pluto (circled) is 13 arcsec from the star 200 minutes before the occultation



Just before occultation: Pluto and star merged, combined light!



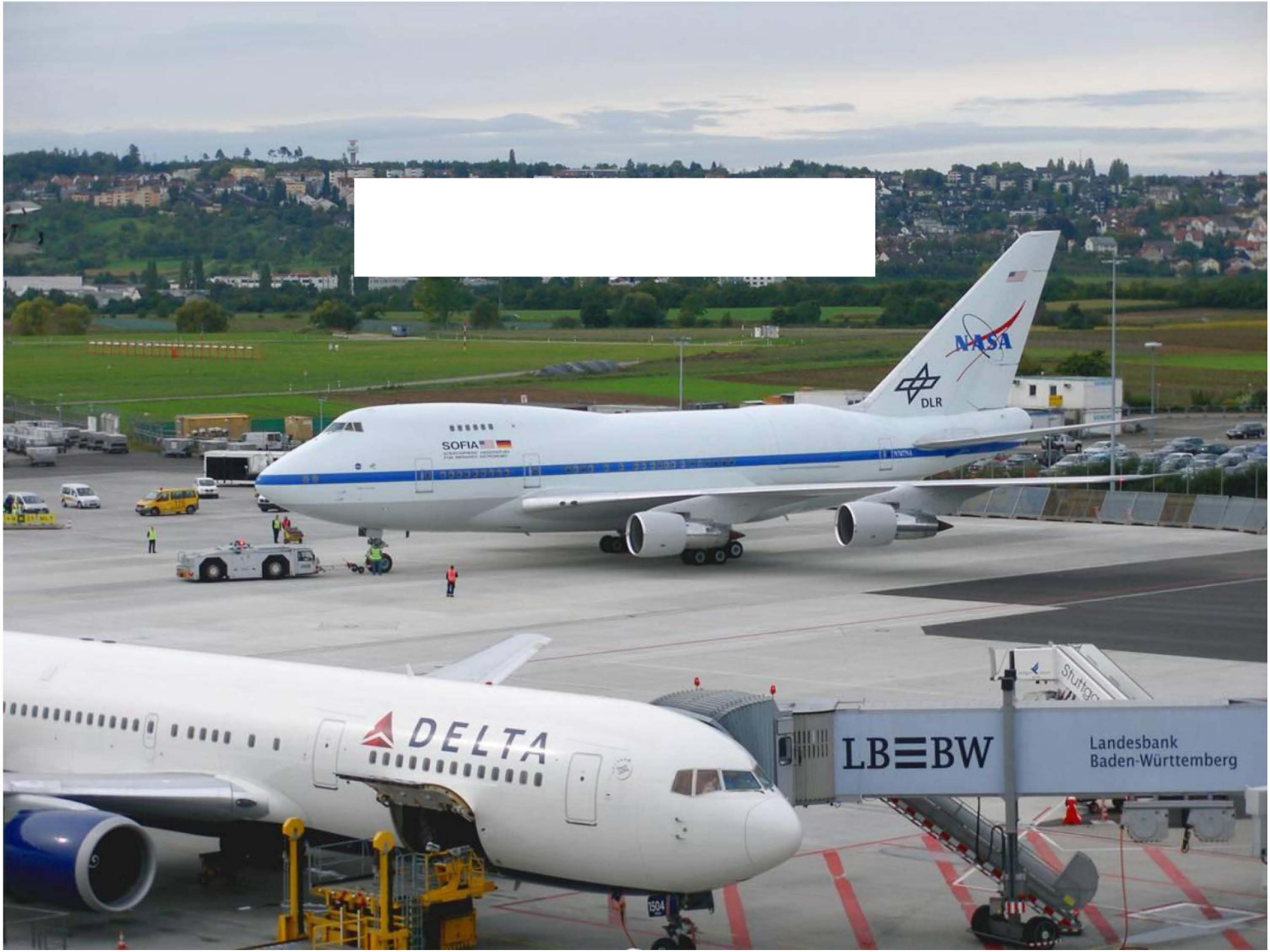
During occultation: Pluto and star merged, only Pluto light seen



After occultation: Pluto and star merged, combined light!

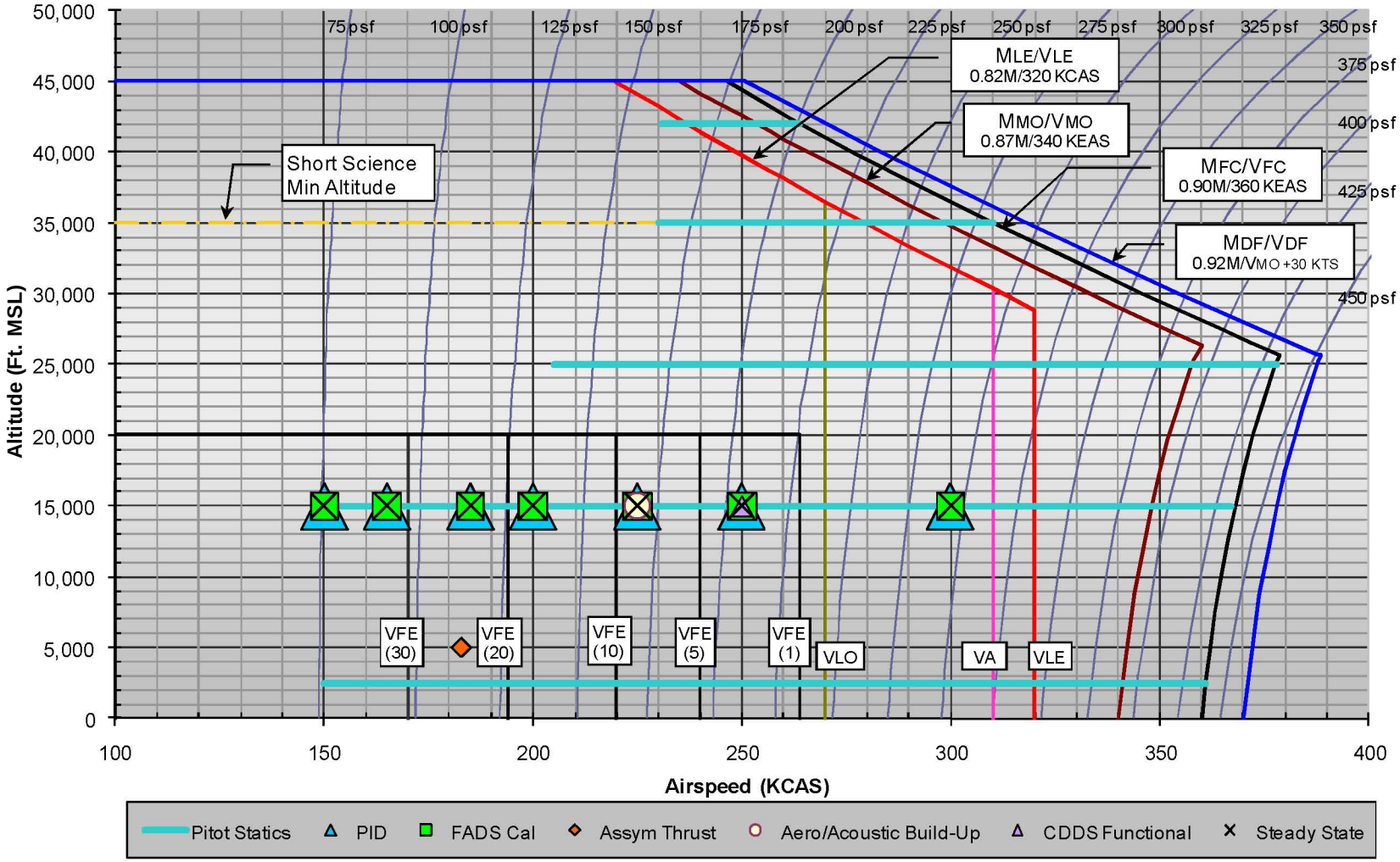
Conclusions/Lessons Learned

1. "Do Your Homework"
 - An investment in baseline, wind tunnel, and ground testing as well as engineering analysis pays large dividends
2. "Schedule for Success, Plan for the Worst"
 - This is more effective if #1 above was sufficiently done
 - Use all tools available to analyze necessary testing
 - Leave plenty of "off ramps" for unknown events
3. Have a Flight Test version of your software
 - Increases test effectiveness
 - May help avoid unknown effects

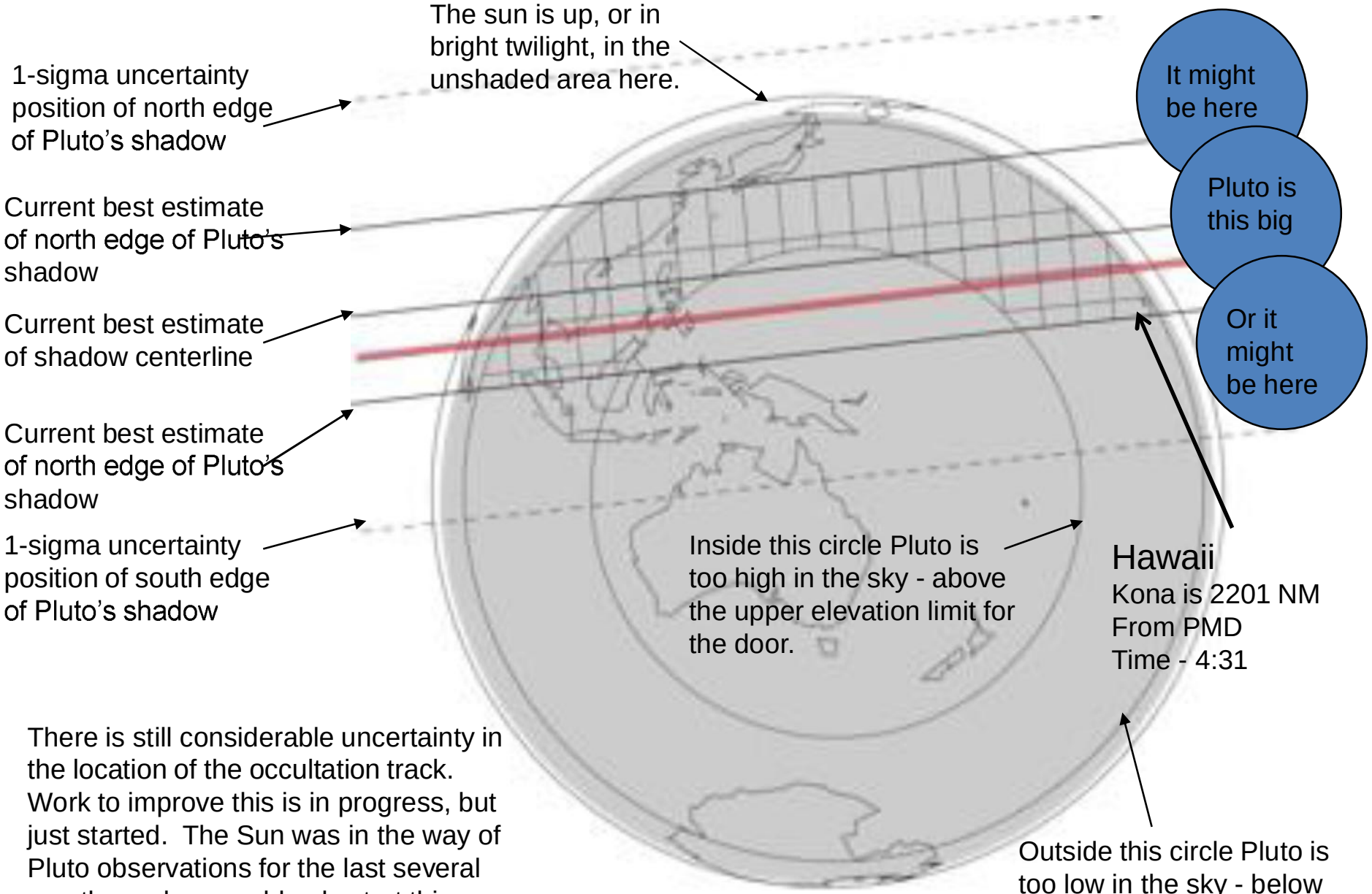

NASA
DLR
SOFIA
DELTA
LBBW
Landesbank
Baden-Württemberg

Backup

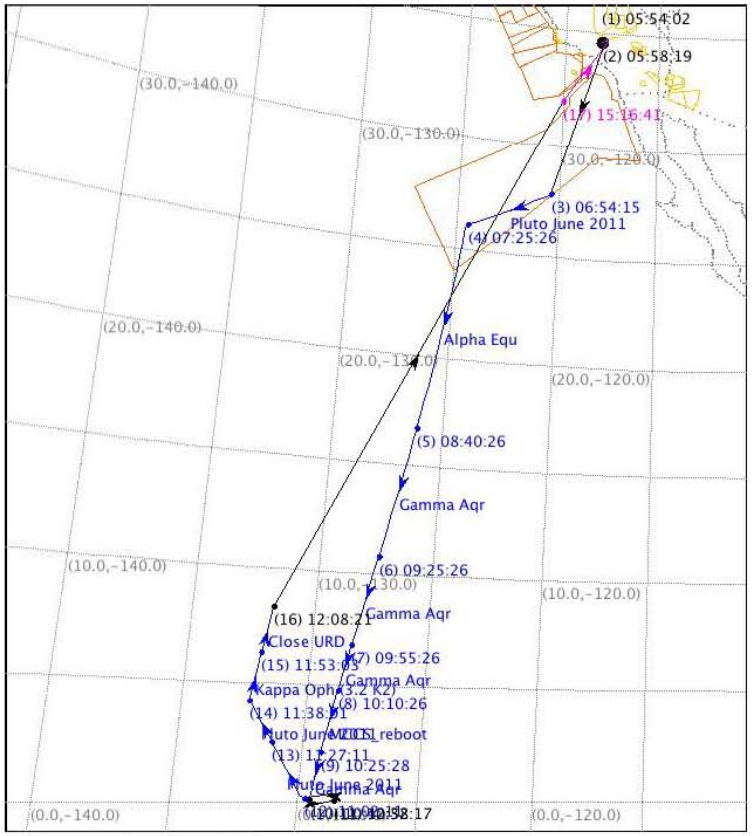
Build-Up to Open Door Envelope Expansion



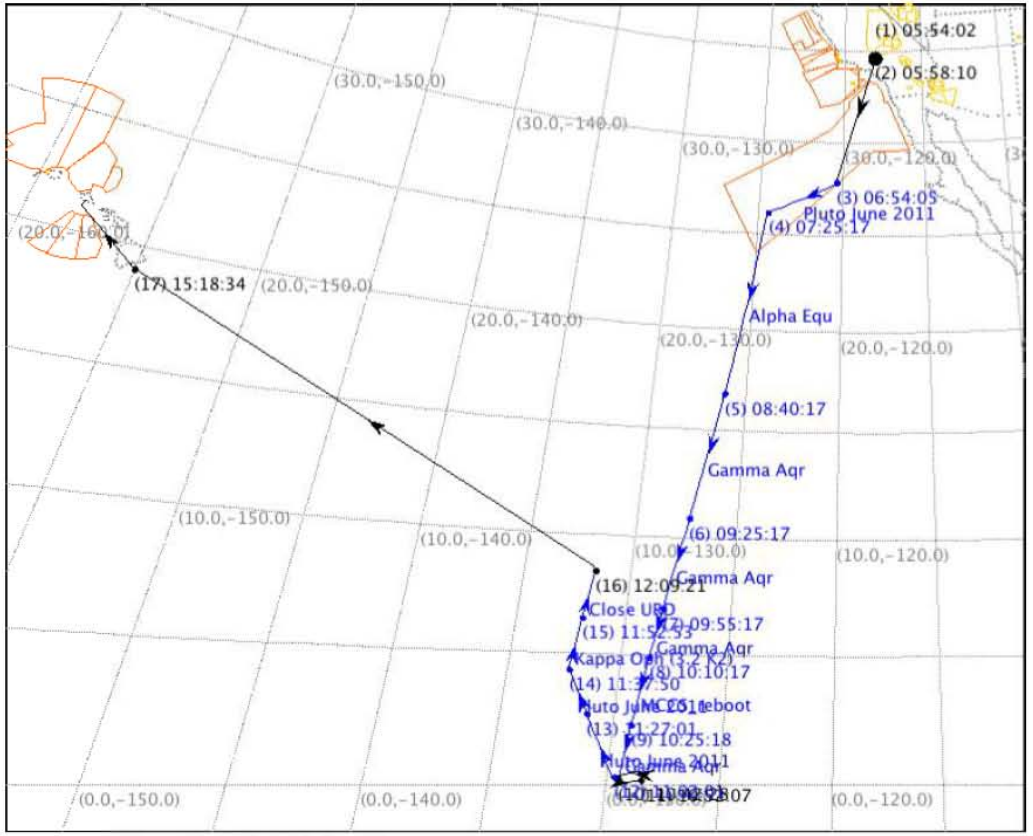
V_{DF}/M_{DF} = maximum demonstrated flight dive speed
V_{FC}/M_{FC} = maximum airspeed for stability characteristics


The sun is up, or in bright twilight, in the unshaded area here.
1-sigma uncertainty position of north edge of Pluto's shadow
Current best estimate of north edge of Pluto's shadow
Current best estimate of shadow centerline
Current best estimate of north edge of Pluto's shadow
1-sigma uncertainty position of south edge of Pluto's shadow
It might be here
Pluto is this big
Or it might be here
Inside this circle Pluto is too high in the sky - above the upper elevation limit for the door.
Hawaii
Kona is 2201 NM From PMD
Time - 4:31
There is still considerable uncertainty in the location of the occultation track. Work to improve this is in progress, but just started. The Sun was in the way of Pluto observations for the last several months and we could only start this work a couple of weeks ago.
Outside this circle Pluto is too low in the sky - below the lower elevation limit for the door.

Latest <u>default</u> version of the flightplan for 06/23/2011



Flight Plan Name: File: SCAI_2_DAOFrtn.fp
Flight ID: 2011/06/23
Est. Takeoff Time: 2011-Jun-23 05:54 UTC
Est. Landing Time: 2011-Jun-23 15:46 UTC
Flight Duration: 09:52
Weather Forecast : 0000 Sun Jun 19 2011 - 1200 Tue Jun 21 2011 UTC
Saved: 2011-Jun-19 07:17 UTC User: ameyer



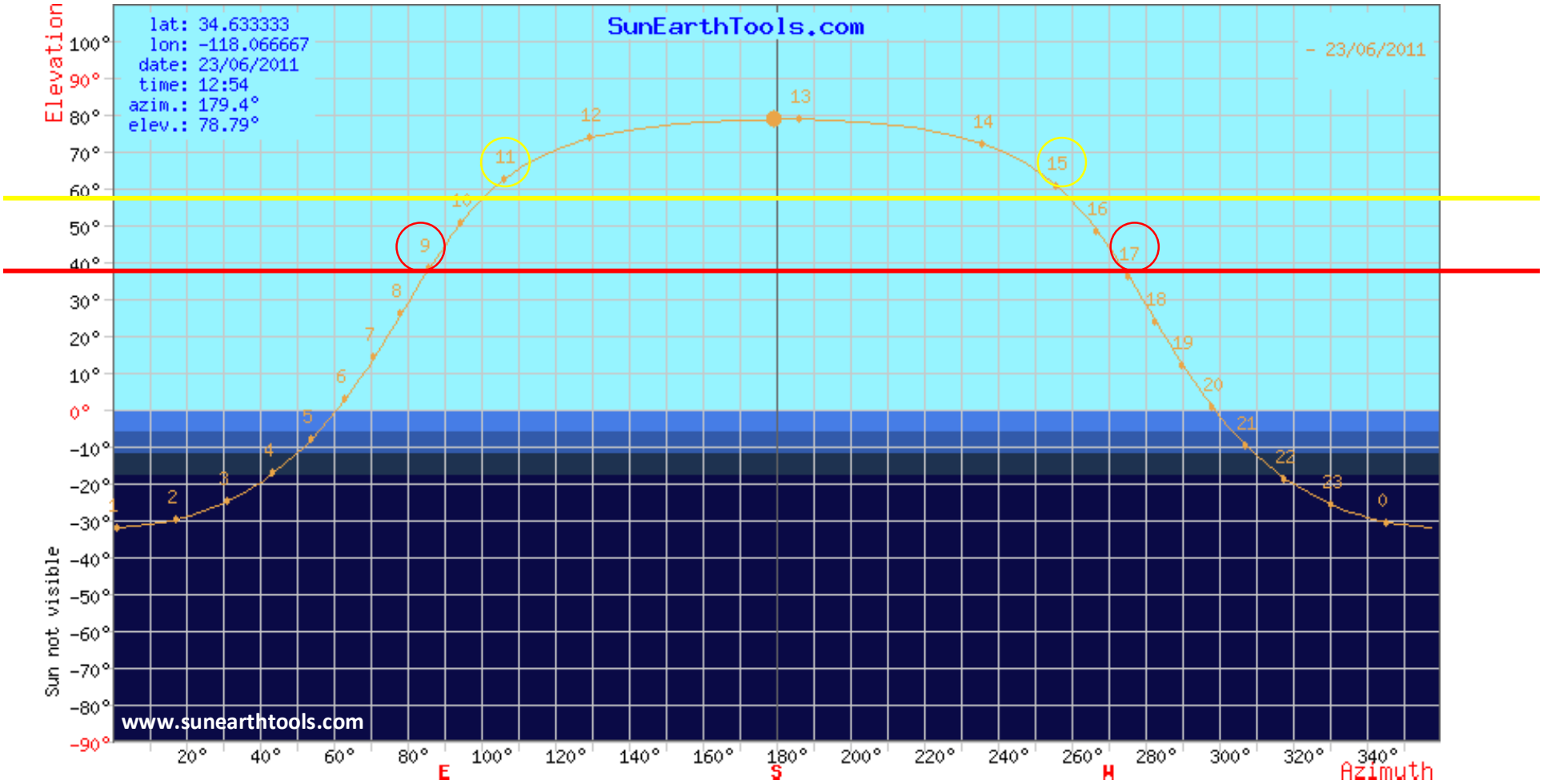
Flight Plan Name: File: SAI2_PHIK_divert.fp
Flight ID: 2011/06/23
Est. Takeoff Time: 2011-Jun-23 05:54 UTC
Est. Landing Time: 2011-Jun-23 15:50 UTC
Flight Duration: 09:56
Weather Forecast : 0000 Sun Jun 19 2011 - 1200 Tue Jun 21 2011 UTC
Saved: 2011-Jun-19 06:10 UTC User: ameyer

➔ In case of an open URD event: landing in HIK is approx. at sunrise

Palmdale

Assuming that CD Dampers will be removed a.s.a.p. after landing and TA will be rotated to 0°:

→ Sun Avoidance Angle in elevation will be 0° + 40° = 40° (red line)



➔ No on ground concern with catching sunlight elevationwise between 9 am and 5 pm

➔ Even with TA in lowest elevation without removing CD Dampers EL=17° (yellow line) the morning hours 9-11 am are not a concern, because TA is facing west (SOFIA's <u>true</u> heading while parking needs to be 0° +/- 20°

There are different options to reach U as final position for engine shut down in PMD:

- straight in approach RWY 07
- straight in approach RWY 04
- before 11 a.m. only: left pattern to RWY 25, taxiing B, A, E

There are different options to reach DFRC as final position for engine shut down in EDW:

- straight in approach RWY 04, taxiing B or C, F, E
- before 9 a.m. only: left pattern to RWY 22, taxiing B or A, E, F

Pilot's in-flight short reference card (1)

True HDGs back to Palmdale from the URD decision point are between 023° and 032°

➔ No enroute concern with catching sunlight, because TA is facing northwest

➔ **Whatever TA elevation, aircraft *TRUE* headings verboten in air or on ground are between 110°T and 225°T (general statement valid before 18 UTC = 11 PDT)**

or in other words:

➔ **True headings allowed in air or on ground are between 226° and 109° (general statement valid before 18 UTC = 11 PDT)**

SUN AVOIDANCE overrules other Open Door Mission Rules to prevent condensation on TA optics/electronics like gradual descent or mirror warm-up holds.

Pilot's in-flight short reference card (2)

Flight Crew should declare an In-Flight-Emergency
when back in VHF Air Traffic Control range, because of limited HDG range
(inability of flying all HDGs, e.g. holding patterns or 360s impossible)

PMD: (max. SOFIA tailwind component is 10 kts)

There are 3 different options to reach Taxiway U as final position for engine shut down:

- straight in approach RWY 07, taxi to taxiway U, **park aircraft with 080° true heading**
 (preferred – easy taxi and easiest go-around)

- straight in approach RWY 04, taxi via E to U, **park aircraft with 080° true heading**
 (second – easy taxi but longer go-around)

- before **11 a.m.** only: two ~90° left turns allowed,
 1) left turn into left base to final RWY 25 (= 265° true HDG)
 2) left turn into final RWY 25,
 taxiing via B, A, E to U,
 park aircraft with 080° true heading

Pilot's in-flight short reference card (3)

In case of a Go-around in PMD, consider a diversion to EDW
(depending on local time, RWY 22 in EDW is only an option before 10 am PDT)

EDW: (max. SOFIA tailwind component is 10 kts)

There are two options to reach DFRC as final position for engine shut down:

- straight in approach RWY 04, taxiing B or C, F, E to DFRC
 park aircraft with 80° true heading

- before **10 a.m.** only: two ~90° left turns allowed,
 1) left turn into left base to final RWY 22 (= 237° true HDG)
 2) left turn into final RWY 22,
 taxiing via B or A, F, E to DFRC
 park aircraft with 80° true heading

Pilot's in-flight short reference card (4)

In case of a Go-around in PMD, consider a diversion to EDW
(depending on local time, RWY 22 in EDW is only an option before 10 am PDT)

If go-around in PMD was RWY 04 or RWY 07:
RWY 22 in EDW is recommended due to timing issues (see map next slide)

- before **10 a.m.** only: two ~90° left turns allowed,
 1) left turn into left base to final RWY 22 (= 237° true HDG)
 2) left turn into final RWY 22,
 taxiing via B or A, F, E to DFRC
 park aircraft with 80° true heading